MOUNTAIN-PLAINS CONSORTIUM

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REMOTE SENSING OF MULTIMODAL TRANSPORTATION ASSETS USING DRONES

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16. Abstract

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Remote Sensing of Multimodal Transportation Assets Using Drones

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ABSTRACT

This comprehensive report synthesizes findings from three distinct yet interrelated studies, each exploring the developing role of drones in the condition monitoring of multimodal transportation assets. The first study, a systematic literature review (SLR) on railway inspection and monitoring (RIM), analyzes 47 articles from a corpus of 7,900 publications spanning 2014-2022. The study identifies cost reduction, safety enhancement, timesaving, and reliability as key motivators for drone adoption in RIM, categorizing applications into defect identification, situation assessment, infrastructure asset monitoring, and others. The second SLR focuses on drone usage in road condition monitoring (D-RCM), surveying 60 articles from 619 publications within the same timeframe. The study reveals similar drivers and categorizes applications into condition monitoring, situation assessment, and construction inspection, while also highlighting challenges such as payload limitations and visual line-of-sight maintenance. The third study introduces a propulsion efficiency index (PEX) for evaluating the performance of drone designs to carry heavier payloads. It establishes range, payload ratio, and aspect ratio as the minimum set of independent parameters for PEX computation, finding that these parameters account for more than 90% of the PEX distribution in the current design landscape. Collectively, these studies offer a multi-faceted analysis of drone applications in transportation, providing critical insights into their technical, economic, and societal implications.

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1. INTRODUCTION

Analysts valued the civilian drone market at $7.4 billion in 2019 and projected that it will reach $22 billion by 2030 [1]. Drones have found diverse applications, including in the transportation sector. Drone technology has emerged as a tool for remote sensing of transportation assets such as roads, railroads, and bridges. When augmented with artificial intelligence (AI) and advanced sensors, drones promise improved data collection by offering speed, cost-effectiveness, and safety. However, the nascent stage of drone deployment in transportation monitoring presents a complex landscape with technological, operational, and regulatory challenges. This research aims to characterize the emerging utility of drones in railway and roadway asset monitoring while characterizing the technology landscape.

Railway Asset Monitoring

The escalating demands of freight and passenger transport require robust investments in railroad infrastructure, particularly in maintenance and safety inspections. Conventional methods, reliant on manual labor or specialized vehicles, are increasingly untenable due to safety risks, financial burdens, and operational inefficiencies. Drone technologies offer a paradigm shift in railroad inspection and monitoring (RIM), enhancing operational efficacy, reducing carbon footprint, and mitigating safety hazards [2] [3]. Despite the burgeoning applications of drones in various infrastructure sectors, there remains a research gap in quantifying their specific utility and cost-effectiveness in RIM, which this study aims to address.

Roadway Asset Monitoring

The state of road infrastructure is a critical economic determinant, with deferred maintenance leading to significant societal costs. For example, in 2019, about 68% of major U.S. roads required immediate attention, costing commuters an estimated $61 billion annually in vehicle expenses and delays [4]. Drones, especially when integrated with real-time kinematic global positioning systems (RTK-GPS) and AI, offer a compelling solution for efficient roadway condition monitoring (D-RCM). However, the literature lacks comprehensive analyses of the quantifiable benefits and challenges of drone deployment in this context.

Propulsive Efficiency Index (PEX)

The landscape of drone designs involves a plethora of options, each with unique performance attributes influenced by patented design choices. The emergence of heavy-lift drones capable of carrying advanced sensor payloads and computing equipment has relevance for both road and rail monitoring. This diversity poses a challenge for stakeholders seeking to evaluate drone performance based on objective metrics. To this end, this research introduces a propulsive efficiency index (PEX), aimed at becoming a standardized metric to encapsulate key performance parameters such as range, payload capacity, and footprint, thereby facilitating a more refined evaluation of drone capabilities.

This multi-faceted research aims to provide a comprehensive understanding of the current and future landscape of drone technologies in transportation monitoring, offering actionable insights for both practitioners and policymakers. The structure of the rest of this report is as follows: Section 2 presents a bibliometric analysis of the existing literature. Section 3 presents the methodology and results of the three research areas. Section 4 outlines the limitations of this study. Section 5 concludes the report and outlines several avenues for future research.

2. LITERATURE REVIEW

The following subsections summarize the results from the literature search in terms of overall benefits and challenges, drone utility in railway condition monitoring, and drone utility in roadway condition monitoring.

2.1 Drone Market Projections

Market projections for drone and advanced air mobility (AAM) technologies indicate significant growth, albeit with varying estimates. For instance, BBC Research anticipates the global drone market to reach \$54.6 billion by 2025, with a compound annual growth rate (CAGR) of 12.7% [5]. Similarly, Brandessence projects global drone revenues to escalate to \$40.9 billion by 2027, based on a CAGR of 12.27% [6]. In the context of the U.S., Deloitte and the Aerospace Industries Association estimate the value of the AAM market at \$115 billion by 2035, constituting 30% of the U.S. commercial aerospace market of 2019 [7].

However, stakeholders should temper these optimistic forecasts by lessons from the slower-than-expected adoption of autonomous vehicles (AVs), attributable to technical and regulatory complexities [8]. Challenges persist, including user acceptance, willingness to pay, integration into national airspace, and infrastructure development for vertiports and fast-charging facilities [7]. Moreover, regulatory frameworks can both catalyze and inhibit innovation [9], and the declining cost of commercial drones raises security concerns [10]. Additionally, the scarcity of critical materials like copper, lithium, and cobalt could escalate battery costs and impact adoption [11].

Adoption is likely to be incremental, with initial applications focusing on areas with high demand and lower technical barriers. Near-term technical constraints, particularly in battery energy density, will confine initial use to short flights [12]. The COVID-19 pandemic has accelerated drone adoption for e-commerce deliveries, suggesting continued growth in this segment [13].

2.2 Utility for Railways

To meet the escalating demands of freight and passenger conveyance, the railroad industry invests significantly in infrastructure, maintenance, and inspection protocols. Ensuring safety and operational efficiency mandates frequent track inspections, traditionally conducted by trained personnel either on foot or using specialized, instrumented vehicles. However, these methods present several limitations, such as human safety risks, considerable expenses, and logistical challenges related to track closures or service disruptions [2].

To address these limitations, the industry is exploring autonomous inspection techniques deploying uncrewed aerial vehicles (UAVs), or drones. These aircraft offer advantages in terms of reduced inspection time, cost-effectiveness through the elimination of specialized training and personnel, and improved safety by removing humans from hazardous environments [3]. Additionally, the use of electrified drones minimizes carbon emissions compared with traditional inspection vehicles like helicopters and hi-rail wagons. Parallel to these developments in the railroad sector, drones have seen accelerated technological advancements [14] and diverse applications, ranging from cargo delivery and agriculture to photogrammetry, surveying, and military surveillance [15] [16] [17] [18] [19]. As a result, the global drone market has witnessed exponential growth, expected to reach a total economic impact of \$30.9 billion by 2028, with a CAGR of 50.2% [20]. The railroad applications market alone achieved a valuation of \$4 billion in 2019, growing annually at a rate of 40% [21]. Given this context, this part of the study aims to critically evaluate the global applicability of drones in the domain of RIM.

2.3 Utility for Roadways

Drone technology plays a multi-faceted role in the surface transportation sector, particularly in monitoring and inspection, traffic enforcement, signal optimization, delivery, and network mapping. The criticality of highway infrastructure to national economies is unquestionable; however, fiscal limitations often result in delayed maintenance activities. Such deferrals, compounded by increased traffic loads and fluctuating environmental conditions, accelerate the structural and functional degradation of pavements before reaching their designed lifespan, thereby escalating eventual maintenance costs [22]. The American Society of Civil Engineers (ASCE) reported in 2019 that 68% of major U.S. roads required immediate attention, costing commuters an estimated $61 billion annually in operational expenses, delays, and incidents [4].

D-RCM has gained prominence, offering enhanced efficiency throughout the RCM process, from data acquisition to analytical decision-making. Real-time kinematic global positioning system (RTK-GPS) significantly improves drone localization [23]. Furthermore, advancements in AI, including deep learning and computer vision, allow for nuanced damage identification based on drone-acquired data.

While several studies have explored the applications of drone technology in transportation asset monitoring, most have been application-specific or focused on machine learning methodologies [24] [25] [26] [27]. There remains an absence of comprehensive research quantifying the benefits and challenges of D-RCM. Therefore, one aspect of this study was to bridge this knowledge gap by identifying and quantifying the specific advantages and limitations associated with D-RCM applications.

2.4 Drone Technology Assessment

The advent of distributed electric propulsion (DEP) has become a pivotal design paradigm in the development of electric vertical takeoff and landing (eVTOL) architectures. DEP enhances aircraft safety and controllability by distributing multiple electric motors around the airframe, each capable of independent speeds and, in some instances, thrust vector adjustments [28]. While DEP offers redundancy and increased maneuverability, it also introduces design complexities, such as the optimization of motor placement and operational characteristics.

Electric motors in eVTOL designs offer several advantages, including efficient energy conversion, ease of distribution for enhanced controllability, and noise reduction—crucial for urban acceptance. However, the design space for eVTOL aircraft is intricate, influenced by variables such as the number of propellers, blade count, fan diameter, and rotational speed. These factors interact in complex ways, affecting overall propulsion efficiency and stability [29].

Current trends indicate a convergence toward winged eVTOL architectures, primarily due to their efficiency in long-range applications [30]. Two predominant winged designs have emerged: vectored thrust and transitioned thrust (TT) architectures [31]. Vectored thrust designs, which include tilt rotor (TR), tilt wing (TW), and folding wing (FW) configurations, offer increased control degrees of freedom but require complex tilting mechanisms. TT architectures, on the other hand, simplify operational complexities by employing separate fixed rotors for lift and cruise, albeit at the cost of carrying idle rotors during cruise, thereby introducing parasitic drag. Manufacturers have explored various strategies, such as retractable propellers, to mitigate this drag [32].

Users favor TR designs for their independent rotor tilting capabilities, but these architectures require sophisticated rotor pitch control systems to manage transient dynamics [33]. TW and FW architectures are less common but offer the advantage of utilizing all rotors for both lift and cruise. However, these designs require trajectory optimization for safe transitions between takeoff and cruise, an area still under active research [34]. Moreover, the battery energy consumption during these transitions is non-trivial, accounting for approximately 8% of the available energy in certain TW designs [35].

2.5 Benefits and Challenges

Advanced drone technology has facilitated a diverse range of applications, including medical supply delivery, insurance risk assessment, agricultural optimization, cargo delivery, and surveying [36] [37] [38] [39] [40] [41]. Nevertheless, challenges persist, such as ensuring human safety during flight failures, payload limitations, battery life constraints, and the absence of comprehensive governmental regulations. Figure 2.1 and Figure 2.2 are infographics that summarize findings from the literature on the overall benefits and challenges, respectively, of using drones in the condition monitoring of multimodal transportation assets.

Improve Safety

- Eliminate inspectors' exposure to hazards and risks
- Reduce the time of inspection
- Inspecting the hard-to-reach places
- Reduce the number of accidents related to lane closure
- Eliminate the subjectivity involved in human inspections
- Reduce the number of people injured in train or car accidents

Save Time

- Drones ascend to higher altitudes
- Reduce the personnel time required
- Can collect multiple tracks simultaneously

Improve Reliability

- High-resolution views
- Comprehensive 360-degree view of the structures

Improve Mobility and Flexibility

- Independence from the land-based infrastructure
- Small size
- Fly remotely
- Travel swiftly from one location to another
- Inspection of hard-to-access areas
- Provide bird's eye view

Reduce Costs

- Reduce data collection time
- Return the current cost of inspecting roads using old methods
- Reduce number of crew
- Reduce the number of safeguards
- Increase capacity
- Reduce traffic shut down
- Reduce operation costs

Figure 2.1 Infographic of the benefits of drone-based monitoring

Technical challenges	– Maintaining a visual line of sight – Limited payload capacity and flight endurance – Lighting conditions – Limited weather resistance – Real-time problems due to severe weather conditions, and distance from the receiver – Drone speed can affect the image resolution – Huge amount of collected data, and sophisticated analysis methods
Regulatory challenges	– Limited speed and altitude – Inadequate regulatory support and industry standards – Absence of regulations applicable to small drones – Prior permission of flying drone – Restriction in flying drones over people
Safety challenges	– Hardware engineering errors like loose connections, faulty electronics – Software engineering errors like programming errors, flawed algorithms, and signal interference – Accidents or falls due to human errors – Collision with a structure while monitoring near it to obtain the best resolution – Drone collisions with field workers – Drone noise distracts workers, which can have secondary safety implications – Cyberattacks
Organizational challenges	– Drone registration – Inadequate capabilities, skills, and experience with drones – Insurance obligations for pilot and drone – Certification and training of pilots

Figure 2.2 Summary of current challenges in drone-based infrastructure condition monitoring

3. METHODS AND RESULTS

The subsections that follow outline the methods and results for each of the three studies. The authors published the first study in the following journal article: Askarzadeh, Taraneh, Raj Bridgelall, and Denver Tolliver. "A Systematic Literature Review of Drone Utility in Railway Condition Monitoring." *Journal of Transportation Engineering, Part A: Systems*, 149(6), DOI:10.1061/JTEPBS.TEENG-7726, March 2023. The second study is currently under consideration: Askarzadeh, T., Bridgelall, R., and Tolliver, D. (2023). "Drones for Road Condition Monitoring: Applications and Benefits." *Journal of Transportation Engineering, Part B: Pavements*. The authors published the third study in the following journal article: Bridgelall, Raj, Taraneh Askarzadeh, and Denver D. Tolliver. "Introducing an Efficiency Index to Evaluate eVTOL Designs." *Technology Forecasting and Social Change*, 191(122539), DOI:10.1016/j.techfore.2023.122539, March 2023.

3.1 Railroad Inspections

Railroads incur significant financial losses from accidents each year. For instance, Table 3.1 lists the accident cause, financial loss, and accident proportion for railway accidents in 2021. Aside from human error, it is apparent that infrastructure related issues caused the most financial loss and number of accidents. Accident causes in the miscellaneous category include environment conditions, loading procedures, highway-rail grade crossing situations, and other unusual operational situations that do not fit into the other categories. Consequently, the recent application of drones in railway condition monitoring has garnered significant attention from both academia and industry. This interest motivated a comprehensive review and analysis of the existing literature to identify the current state of research, potential gaps, and future directions.

Table 3.1 FRA reported financial losses from railway accidents in 2021

Accident Cause	Financial Loss	Accident Proportion
Human error	$90 million	37.2%
Track & roadbed problems	$84 million	22.6%
Equipment & signal problems	$59 million	11.3%
Highway-rail grade Crossing	$14 million	9.7%
Miscellaneous	$1.8 million	17.7%

This section reports the results of an exhaustive systematic literature review (SLR) that the authors conducted on the application of drones in railway infrastructure monitoring (RIM). The SLR methodology, outlined in Figure 3.1, assured a systematic, transparent, rigorous, unbiased, and repeatable approach to the analysis. The SLR scrutinized a corpus of literature obtained from Google Scholar and Scopus databases, as illustrated in Figure 3.2, which shows the distribution of articles by publisher and year. Figure 3.3a offers a descriptive breakdown of the selected papers by year and by country of origin and Figure 3.3b provides an alternative visualization by country and year. Figure 3.4 shows the distribution of RIM articles by research methods and year. The patterns reveal a growing interest in this research area.

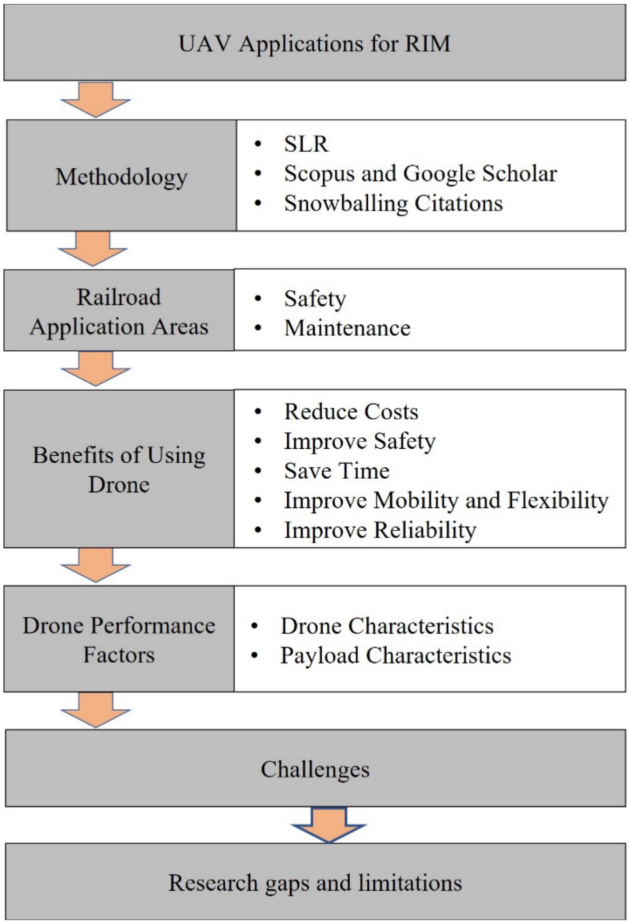

Figure 3.1 Workflow of the SLR methodology

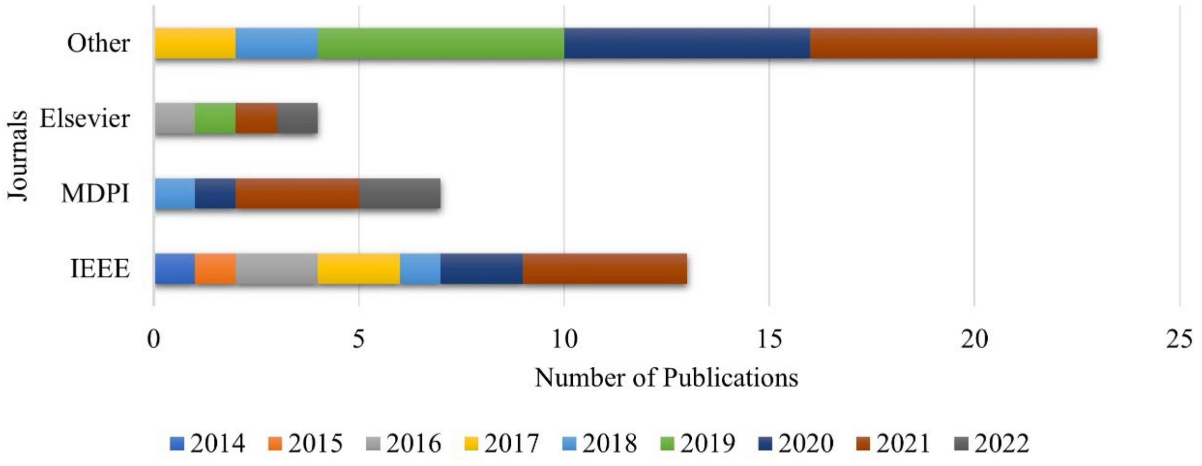

Figure 3.2 RIM articles by publisher and year

The SLR classified RIM application of drones into five different areas, with their distribution by year shown in Figure 3.5. Most of the studies focus on railway infrastructure asset monitoring, defect identification, and risk assessment. Figure 3.6 further elucidates the distribution of papers by country and application, highlighting the global interest and varied focus in this research area. Studies from China focus on infrastructure asset monitoring, while those from the United States cover a broader range of applications, including defect identification and risk assessment. Table 3.2 provides a further classification of those applications into the three broader categories of maintenance, safety, and security.

Figure 3.7 shows the distribution of payload types used. Most of the studies employed visual cameras, while a smaller fraction used advanced sensors like LiDAR and RFID. This diversity in payload types indicates the versatility of drone technology in addressing different railway monitoring needs. Table 3.3 summarizes the benefits of using drones for RIM, and Table 3.4 summarizes the cost areas. Table 3.5 summarizes the challenges and open issues in the field, emphasizing the nascent stage of this technology. The categorization of benefits and the identification of challenges provide valuable insights for railway operators and drone manufacturers. The information can guide the development of more efficient and specialized drone systems for railway condition monitoring.

The SLR identified several research gaps, particularly in the areas of drone autonomy, data analytics, and integration with existing railway monitoring systems. These gaps present opportunities for future academic research. As drone technology matures, the industry will need comprehensive policies that govern the use of drones in critical infrastructure monitoring. In summary, this research laid the groundwork for future scholarly endeavors in this domain.

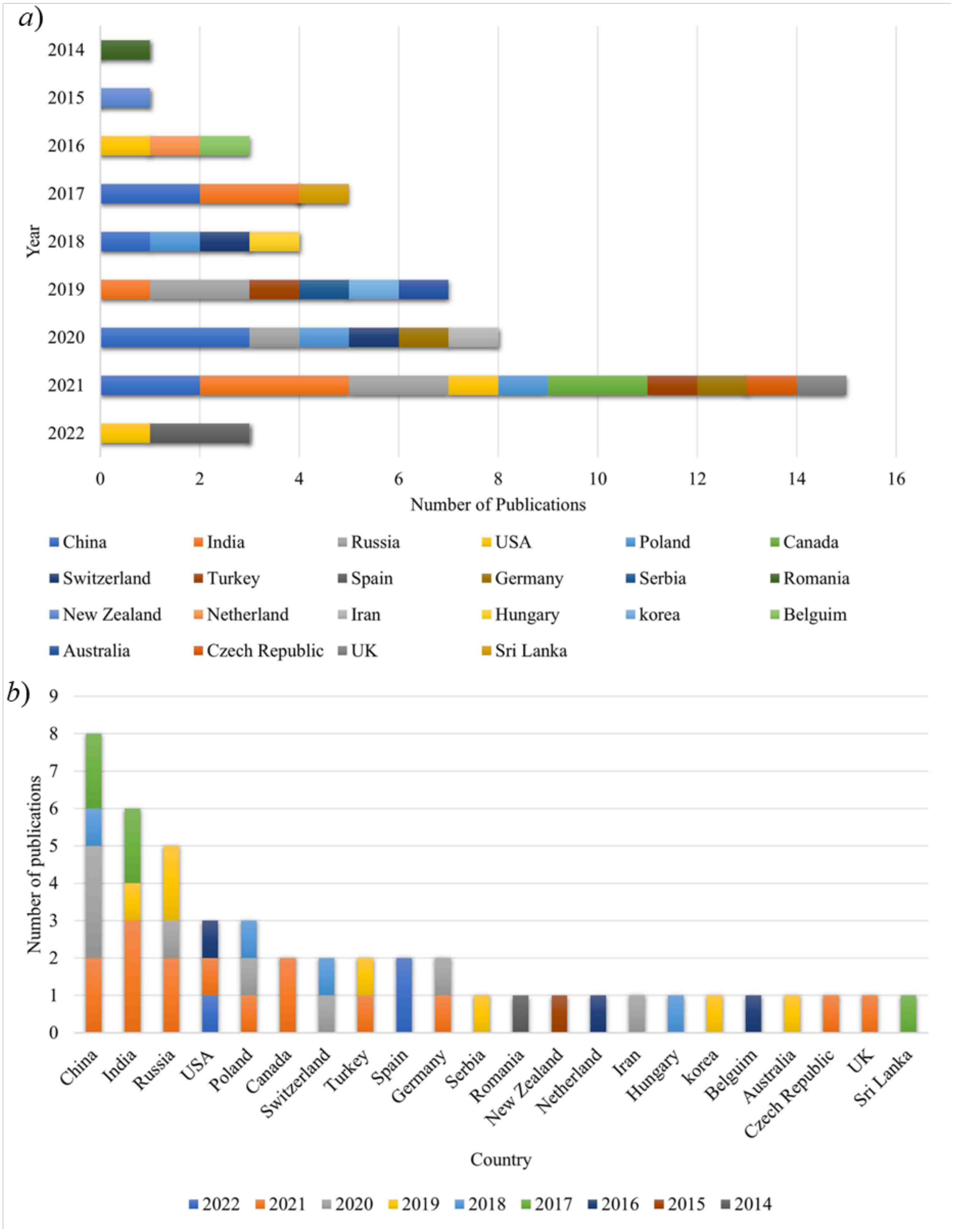

Figure 3.3 RIM articles by a) year and country and b) country and year

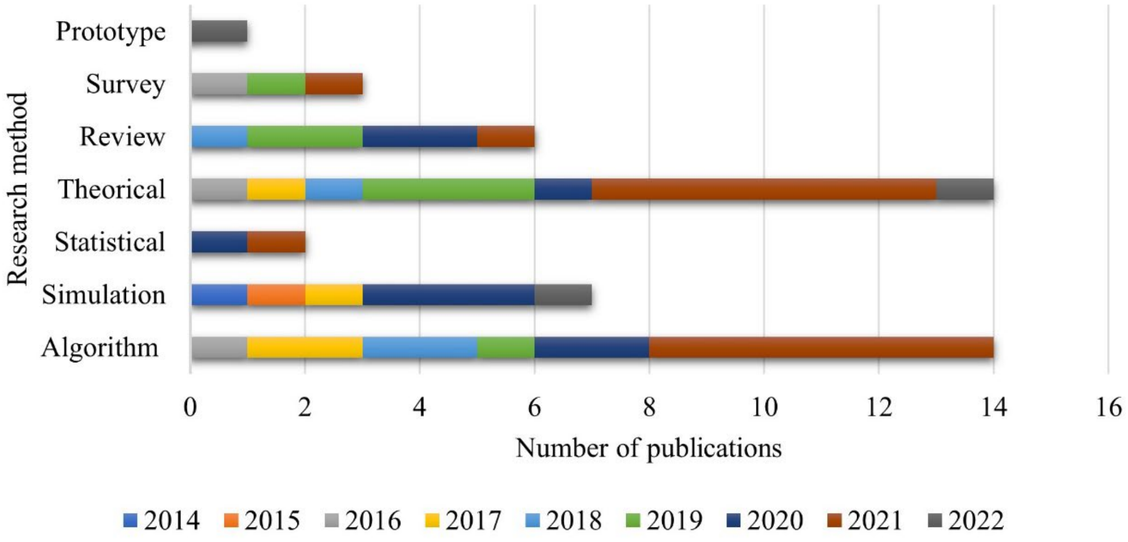

Figure 3.4 RIM articles by research methods and year

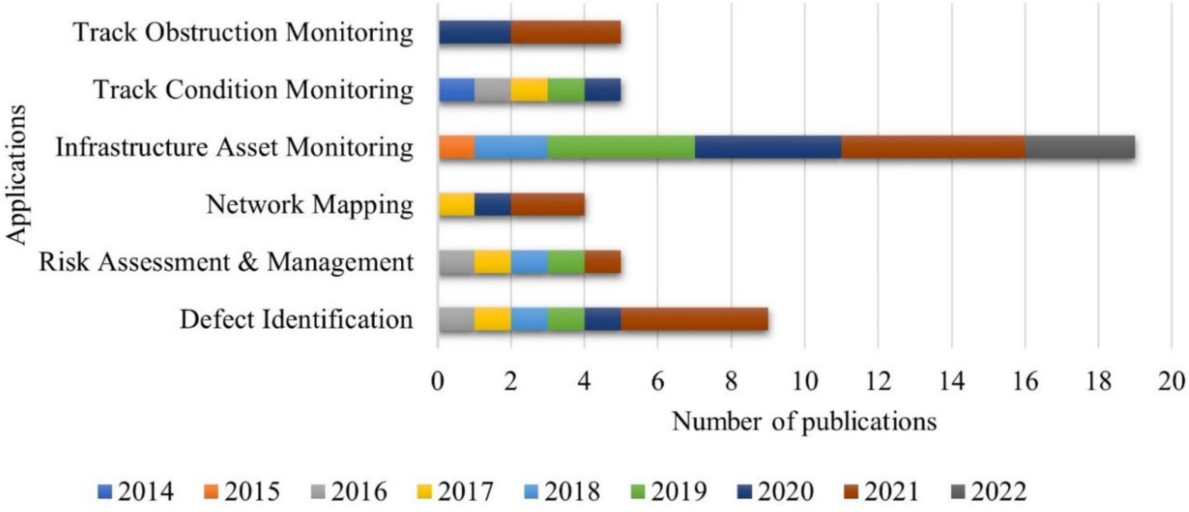

Figure 3.5 RIM articles by application and year

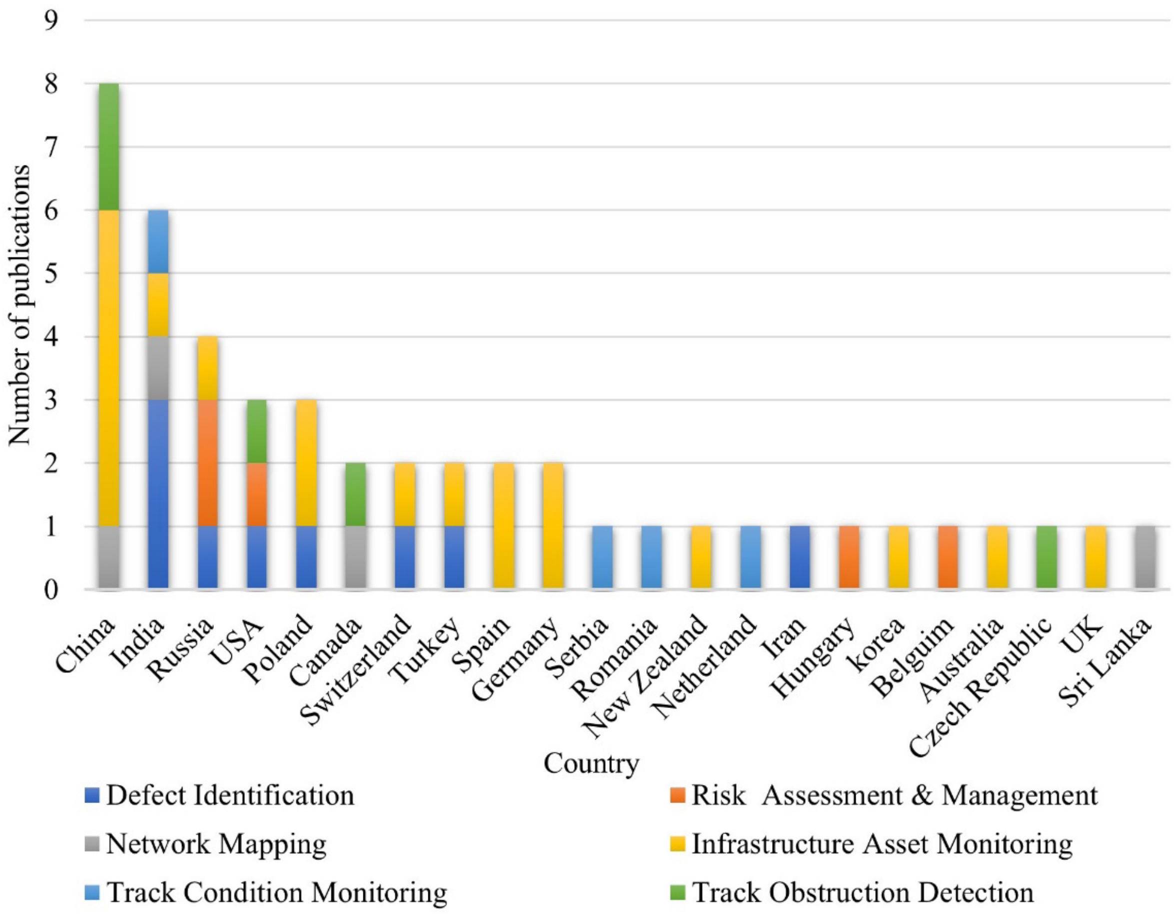

Figure 3.6 RIM articles by country and application

Table 3.2 Application Classification for Railroads

Safety & Security	Maintenance
Defect Identification of Tracks • Irregular Track Geometry • Rail Defects Risk Assessment & Management • Evaluate Accident Scenarios • Evaluate Vulnerabilities • Evaluate Risks from Natural Hazards Trespassing Detection Monitoring Grade Crossing Theft Monitoring Network	Mapping Surveying Navigation Graffiti Removal Track Condition Monitoring • Railway Embankment Monitoring • Track Structure Monitoring Infrastructure Asset Monitoring • Railway Tunnel Monitoring • Rail Bridge Monitoring • Railway Infrastructure Monitoring • Equipment Monitoring • Railway Contact Wire Monitoring • Inspection of Roofing and Stations Track Obstruction Detection • Storage of Materials Along the ROW Rockfall, Vegetation, and Water Accumulation

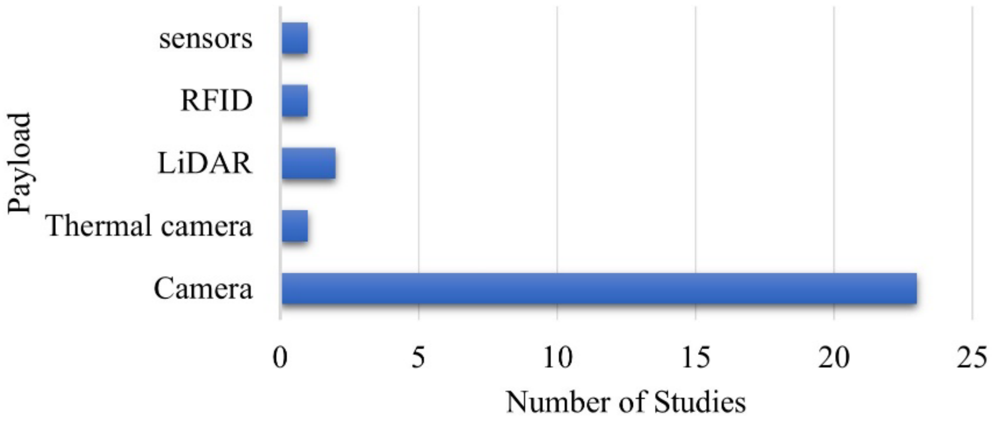

Figure 3.7 Type of payloads used in the reviewed studies

Table 3.3 Benefits of Using Drones for RIM

Potentials	**Areas**	**Description**
Reduce Costs	Improve safety Reduce time Return the current cost of inspecting railways using old methods	Reduce the number of safeguards Reduce the cost of accidents caused by deteriorating railways Reduce the number of people employed to support the inspection and monitoring process Increase capacity Increase in efficiency by 10% Energy saving 20% Up to four tracks can be monitored simultaneously Reduce drivers' costs Reduce the requirement for traffic shut down Reduce operation costs by 50%
Improve Safety	Produce higher-resolution, precise imagery Nondisruptive technology of drones Reduce accidents	Reduce the risk of overlooking the defects Improve the quality of monitoring Conduct more frequent inspections and gather more data Inspecting the hard-to-reach places Reduce the amount of time inspectors need to be on the rails and increase safety Reduce the number of people injured in the train accidents
Save Time	Drones ascend to higher altitudes	Can collect multiple tracks simultaneously
Improve Mobility and Flexibility	Independence from the land-based infrastructure Small size Fly remotely	Travel swiftly from one location to another Inspection of hard-to-access areas Provide bird's-eye view
Improve Reliability		High-resolution views Comprehensive 360-degree view of the structures

Table 3.4 Cost Areas of Using Drones for RIM

	Cost area	Recurring	Location	Details
Equipment	Drone component			
	Airframe	Once	Drone	-
	Battery	Once	Drone	-
	Auxiliary components			
	Regulators	Once	Drone	-
	Parachute	Once	Drone	-
	Cables	Once	Drone	-
	Power management electronics	Once	Drone	-
	Memory chips	Once	Drone	-
	RC receiver	Once	Ground	-
	Radios	Once	Ground	-
	Flight Ops management software	Once	Ground	-
	Drone control and image acquisition			
	Sensor	Once	Drone	-
	Camera	Once	Drone	-
	Telemetry kit	Once	Drone	-
	TX radio control	Once	Ground	-
	Flight terminator	Once	Drone	-
	Data modem	Once	Ground	-
	Ground control Station			
	Monitors	Once	Ground	-
	Network hub	Once	Ground	-
	Image process	Once	Ground	-
	Streaming server	Once	Ground	-
	RC transmitter	Once	Ground	-
	Telemetry kit	Once	Ground	-
	HDMI splitter	Once	Ground	-
	UAV landing pad			
	Wi-Fi router	Once	Ground	-
	Telemetry radio	Once	Ground	-
	Control board	Once	Ground	-
	NEMA box	Once	Ground	-
	Installation service	Once	Ground	-
Staffing	UAS pilot	Monthly	Ground	Recommended at least an FAA instrument-rated pilot.
	Co-pilot or observer	Monthly	Ground	Part 91 operations require class 2 FAA medical certificates.
	Maintenance team	Monthly	Ground	
	Data analyst	Monthly	Ground	Will manage the data acquired by drone.
Resources	Cost of training and staff turnover	Monthly	-	-
	Cost of aviation insurance and safety management	Monthly	-	-
	Registering the drone with the Federal Aviation Administration (FAA)	Once	-	-
	Liability insurance	Monthly	-	-

Table 3.5 Challenges of Drones in RIM

Challenges	Description
Technical challenges	Maintain visual line of sight Payload capacity and flight endurance are limited Limited weather resistance Collisions and interference Rapid battery discharge Lighting conditions Non-uniform illumination and noise corruption Small objects are difficult to detect
Safety challenges	Loss of control of the UAV Non-controlled ground impact Collision with someone Fatal injury to someone The threat of espionage and terrorism
Regulatory challenges	Inadequate regulatory support and industry standards Regulatory uncertainty and barriers Absence of regulations applicable to small drones
Organizational challenges	Investing in supporting infrastructure takes time and money Inadequate capabilities, skills, and experience with drones Insurance obligations Certification and training of pilots

3.2 Roadway Inspections

This section reports on the results of a systematic literature review on the increasing use of drones in road condition monitoring (D-RCM). The study quantified the benefits and challenges of D-RCM by surveying 60 articles from a pool of 619 publications between 2014 and 2022. Figure 3.8 shows the workflow for the literature review methodology. Table 3.6 summarizes the application classification for roadways.

Key findings of the study were that the primary drivers for adopting D-RCM are cost and time savings, safety enhancements, improved mobility, and reliability. The authors categorized D-RCM applications into condition monitoring, situation assessment, network mapping, asset monitoring, and construction inspection. The study reveals considerable cost benefits and an impressive ROI of up to 980%. Challenges include maintaining visual line-of-sight, limited flight time, payload capacity, and engineering errors. Potential solutions include terrain-following features, optimizing battery capacity-weight balance, and employing trained personnel.

Table 3.6 Application Classification for Roadways

Safety & Security	Maintenance
Risk Assessment • Evaluating risks natural hazards • Evaluating risks on harsh roads Landslide Monitoring • Landslide hazards monitoring • Slope stability monitoring Construction Inspection • Monitoring road construction sites • Monitoring forest roads Environmental Monitoring (green belts) Intersections Monitoring	Parking Monitoring Retaining Walls Monitoring Unpaved Road Condition Monitoring • Stone and gravel pavement condition monitoring • Unpaved roads monitoring and prioritizing Pavement Condition Monitoring • Surface defect detection • Pavement distress monitoring Network Mapping Bridge Inspection • Concrete bridge crack detection • Bridge crack inspection • Bridge inspection in harsh operating environment • Bridge condition assessment

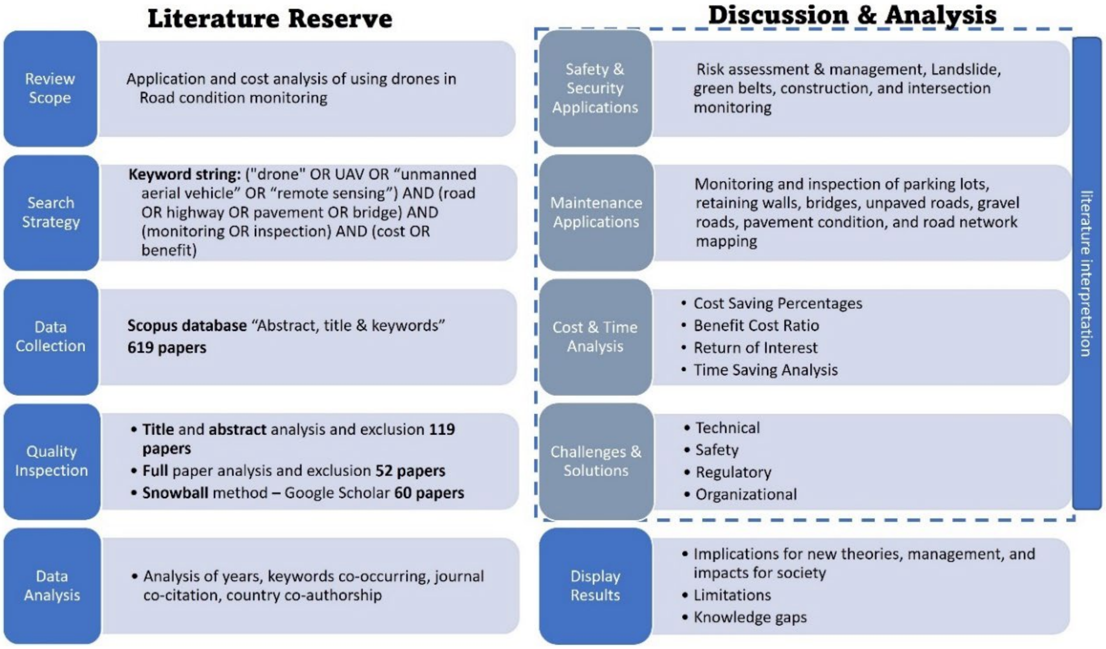

Figure 3.8 Flow diagram of the methodology applied in this review

Figure 3.9 provides a visual representation of the distribution of publications from 2014 to 2022. It shows the growth in attention toward monitoring and safety applications using drones. The figure shows the temporal trends in the field, highlighting that the peak of publications occurred in 2020.

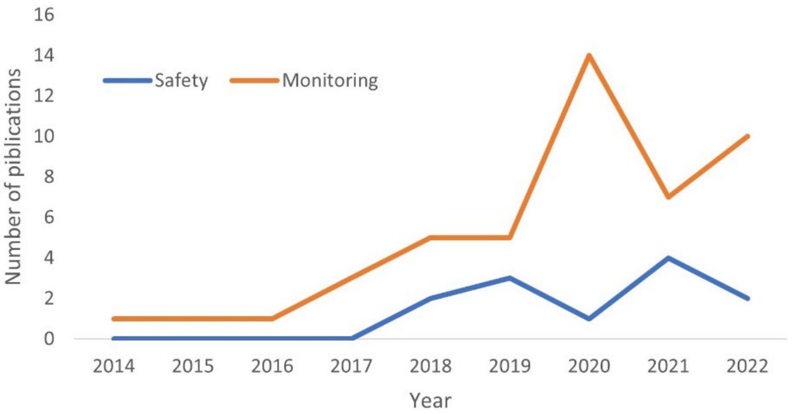

Figure 3.9 The distribution of retrieved publications based on the applications by year

Figure 3.10 is a visualization that shows the timeline of clustered keywords in the field of D-RCM from 2014 to 2022. It uses nodes to represent keywords and links to show their connections. The size and color of the nodes indicate the popularity and emergence of specific research topics over time. This figure serves as a roadmap for understanding the evolution and current focus areas in D-RCM research.

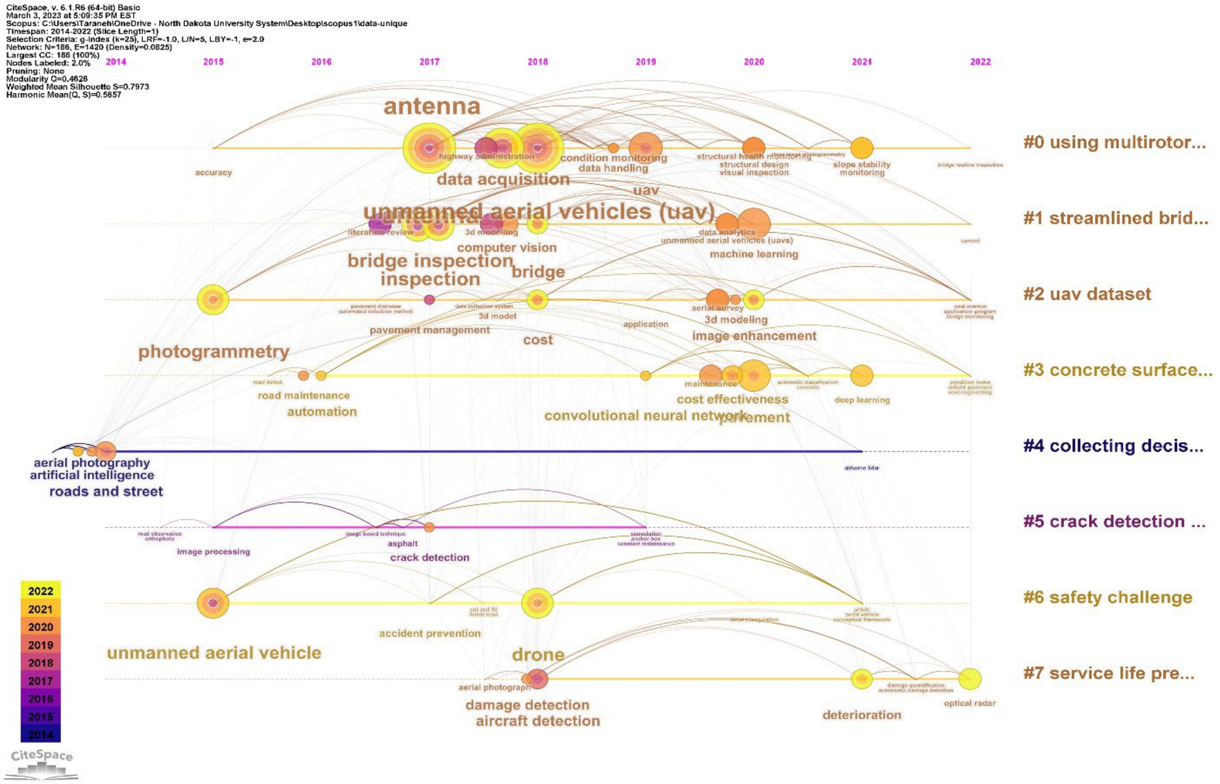

Figure 3.10 Keyword co-occurrence network of D-RCM

Table 3.7 complements Figure 3.10 by providing a detailed breakdown of the keyword clusters. It lists the Cluster-ID, size, silhouette value, year, and log-likelihood ratio (LLR) label for each cluster. This table is crucial for understanding the specific research areas that are currently at the forefront of D-RCM. Table 3.8 presents the top 18 keywords with the most significant citations.

Table 3.7 Clusters by Keyword in the Study of D-RCM

Cluster-ID	Size	Silhouette	Year	LLR Label
0	40	0.694	2019	Using multirotor unmanned aerial vehicle
1	28	0.763	2018	Streamlined bridge inspection system
2	26	0.729	2019	Dry-stone masonry
3	24	0.785	2019	Concrete surface crack
4	22	0.978	2014	Collecting decision support system data
5	18	0.9	2017	Crack detection classification
6	16	0.833	2019	Safety challenge
7	12	0.862	2019	Service life prediction

Table 3.8 Top 18 Keywords with the Most Robust Citation Burst from 2014 to 2022

Keywords	Year	Strength	Begin	End
Aerial photography	2014	1.17	2014	2019
Image processing	2014	1.19	2015	2017
Pavement management	2014	1.49	2017	2018
Federal Aviation Administration	2014	0.99	2017	2018
Aircraft detection	2014	1.3	2018	2019
Highway administration	2014	1.14	2018	2018
Three-dimensional computer graphics	2014	1.14	2018	2018
UAV	2014	1.84	2019	2020
Machine learning	2014	1.28	2020	2020
Computer vision	2014	1	2020	2020
Cost-effectiveness	2014	1	2020	2022
Pavement	2014	1.76	2021	2022
Deterioration	2014	1.5	2021	2022
Convolutional neural network	2014	1.23	2021	2022
Photogrammetry	2014	1.06	2021	2022
Deep learning	2014	1.04	2021	2022
Slope stability	2014	1.04	2021	2022
Monitoring	2014	1.04	2021	2022

Figure 3.11 visualizes the co-citation relationships between scholarly journals in the field of D-RCM. Each node represents a journal, and the size of the node indicates its citation count. The figure is instrumental in understanding the academic landscape and identifying the most influential journals in D-RCM research. Table 3.9 ranks journals based on the intensity of their citations. It provides the journal name, year, strength, and the period during which they occurred. This table helps identify the journals that have recently gained prominence in D-RCM research.

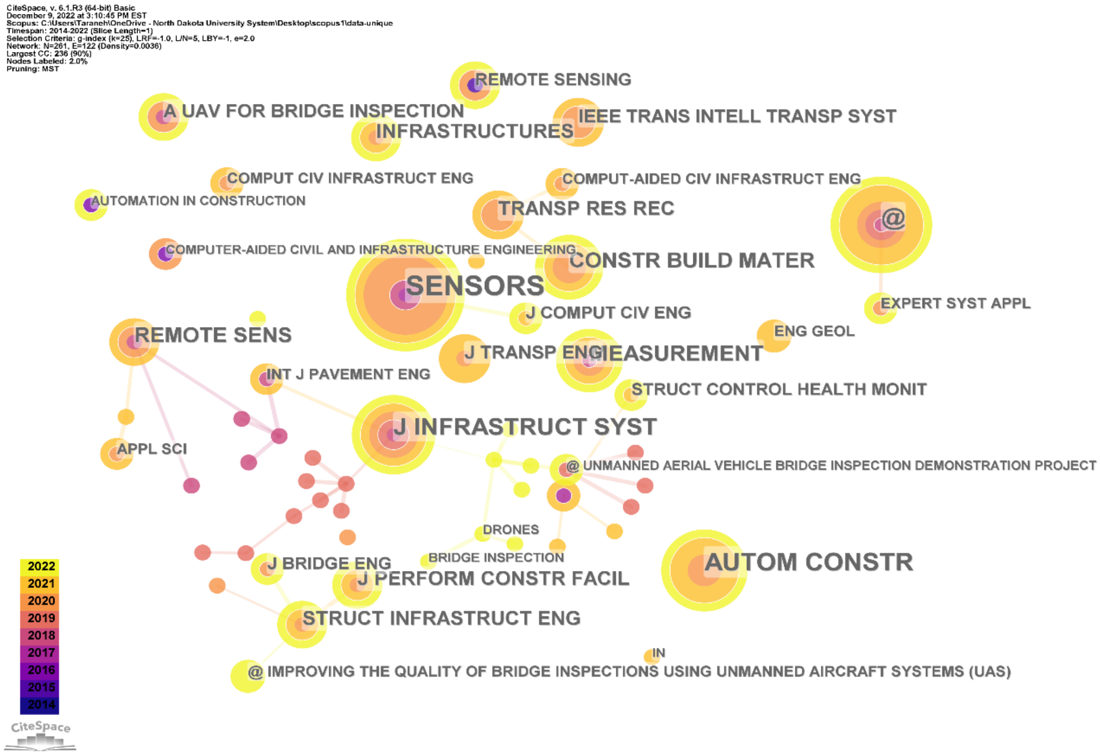

Figure 3.11 Map of cited journals co-citation network in D-RCM

Table 3.9 Top 8 Cited Journals with the Strongest Citation Bursts

Cited Journals	Strength	Begin	End
Sensors	2.5	2020	2020
Automation in Construction (AUTOM CONSTR)	1.97	2020	2022
Engineering Geology	1.87	2021	2022
Transportation Research Record (TRANSP RES REC)	1.67	2020	2022
IEEE Transportations on Intelligent Transportation Systems	1.43	2020	2022
Journal of Transportation Engineering (J TRANSP ENG)	1.43	2020	2022
Infrastructures (IN)	1.4	2021	2022
Journal of Management in Engineering (J MANAG ENG)	1.4	2021	2022

Table 3.12 shows a network of country co-authorship in D-RCM research. The size of each node represents the number of papers published by that country. This figure is essential for understanding the global distribution of D-RCM research and identifying which countries are most active in this field. Table 3.10 lists the top 11 countries by publication volume in D-RCM. It provides the country name, frequency of publications, centrality score, and the year they started publishing in this field. This table offers a quantitative view of countries leading in D-RCM research.

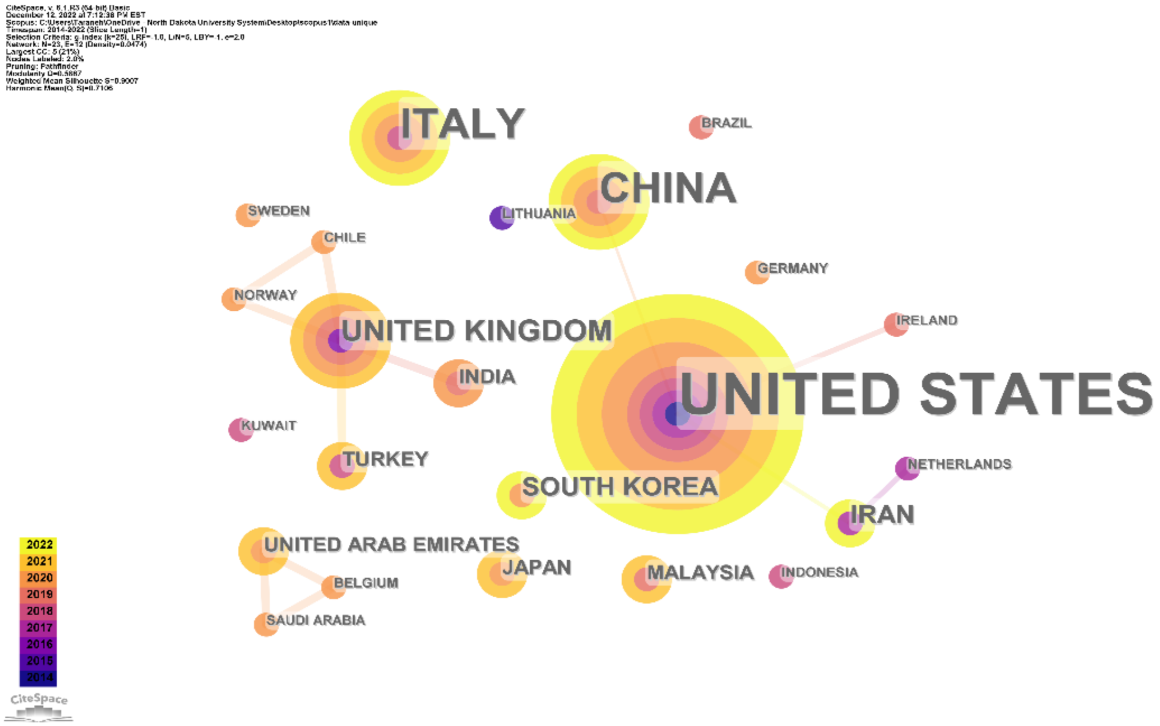

Figure 3.12 Visualization network map of the country co-authorship analysis

Table 3.10 Top 11 Dominant Countries of D-RCM Articles

Sr. No.	Country	Freq	Centrality	Year
1	United States	22	0.04	2014
2	China	8	0	2018
3	Italy	8	0	2019
4	United Kingdom	4	0.04	2016
5	South Korea	3	0	2020
6	Iran	2	0.03	2017
7	United Arab Emirates	2	0	2020
8	Turkey	2	0	2018
9	Malaysia	2	0	2019
10	Japan	2	0	2020
11	India	2	0	2019

Table 3.11 provides a comprehensive guide to the safety applications in D-RCM. It provides details on the types of drones used, the sensors employed, and the algorithms or software discussed in the relevant papers reviewed.

Table 3.11 Safety Benefit Areas of D-RCM

Benefit Area	Categories	Drone	Sensor	Algorithm/ Software
Risk Assessment	**Evaluating risks natural hazards**	**Fixed wing and multi rotor**	**-**	**MATLAB**
		-	**-**	**UAV-CRP**
	Evaluating risks on harsh roads	**Fixed-wing drone**	**-**	**Agent operator mode simulation**
Landslide Monitoring	**Landslide hazards monitoring**	**-**	**4K camera**	**-**
	Slope stability monitoring	**-**	**NIKON D800E, CMOS full-frame sensor**	**AMS software**
Construction Inspection	**Monitoring road construction sites**	**DJI Phantom 4 RTK**	**-**	**Pix4DMapper**
		DJI Phantom 4 Pro	**V2.0 High-resolution camera and thermal sensors**	**-**
		DJI Phantom 4 RTK	**RTK GNSS**	**AutoCAD**
		-	**-**	**-**
	Monitoring the construction of forest roads	**DJI Phantom 4**	**-**	**Pix4D Capture**
Environmental Monitoring	**Monitoring green belts**	**-**	**ZENMUSE X5 camera**	**-**
Intersections Monitoring	**Intersections monitoring**	**DJI Matrice 200**	**-**	**DJIGO 4 app**

This table categorizes the safety applications into various benefit areas such as risk assessment, landslide monitoring, construction inspection, environmental monitoring, and intersection monitoring. Papers on risk assessment focused on monitoring the flow of vehicles and changes in routing parameters after floods. This category of work is particularly important for management to redefine problems and reroute vehicle flow under new parameters. Papers evaluating risks on harsh roads proposed new methods for path following in dangerous areas like jungles and mountains. Such solutions incorporated fixed-wing drones and algorithms to allow a drone to analyze its past path and continue flying in case of lost communications with the operator. Papers covering landslide monitoring utilized drones equipped with 4K cameras to monitor landslide hazards. These studies provided valuable data on affected areas and the presence of saturated debris material. Studies on slope stability monitoring obtained geometrical data on discontinuities along the entire road, enabling the definition of potential kinematic mechanisms. Studies about monitoring road construction sites, such as along expressways, employed drones like DJI Phantom 4 RTK and used software like Pix4DMapper and AutoCAD for data analysis. Studies monitoring construction of forest roads aimed to assess the feasibility and economic benefits of using drones for this purpose. Studies about monitoring green belts quantified influential factors in aerial photography route design for highway green belts monitoring. Studies on intersection monitoring demonstrated the use of drones coupled with UAV-CRP technology for fast, safe, and efficient identification of obstructions within intersection sight triangles.

Table 3.12 (part I) and Table 3.13 (part II) summarize the scope of maintenance applications in D-RCM. It categorizes the applications into several benefit areas such as parking monitoring, retaining walls monitoring, bridge inspection, unpaved road condition monitoring, pavement condition monitoring, and road network mapping.

Table 3.12 Maintenance Benefit Areas of D-RCM (Part I)

Benefit Area	**Categories**	**Drone**	**Sensor type**	**Algorithm/ Software**
Parking Monitoring	Parking lot monitoring	DJI Mavic PRO	Camera	RMSE/refAT
Retaining Walls	Pile retaining walls monitoring	DJI PHANTOM 3 Pro	12-megapixel camera	I-Site Studio, 3D Reshaper/LAZ
		DJI Matrice 600 Pro	-	Pix4Dmapper
		DJI Mavic 2	Camera	-
		DJI Mavic 2	-	-
			LiDAR SLAM	R-CNN
		DJI phantom 4	Camera	NNS algorithm/SfM
		DJI S800	Sony NEX-7	SGM/ FANN
		DJI Mavic	Gimbaled	-
		COTS airframe	24 megapixel A6000 digital SLR camera	-
		-	-	PHP/MySQL/ iBIRD
		-	-	3D point clouds/GNSS
		DJI Matrice 300	LiDAR DJI Zenmuse	GNSS signal obstruction
	Bridge inspection in harsh operating environment	DJI Matrice 100/ DJI Phantom 4 Pro V2.0	Zenmuse Z3 camera/DJI remote controllers	-
	Concrete bridge crack detection	low-cost quadrotor		SVM/ Raspberry Pi 3 Model B
	Bridge crack inspection	DJI Phantom 4 Pro	Ricoh/Theta V 360	-

The table provides details on the types of drones used, the sensors employed, and the algorithms or software discussed in the relevant collection of papers. Papers about monitoring parking lots using drones equipped with a camera utilized software for real-time drone mapping to significantly improve processing time and accuracy, enabling quick and safe inspections without disrupting the facility's operations. Papers on retaining wall monitoring demonstrated the use of photogrammetry to produce precise 3D models of masonry retaining walls. This method can identify local areas subject to failure and aid maintenance efforts, ensuring public safety while minimizing costs. Studies on bridge condition assessment, including in cold environments, demonstrated the utility of drones like the DJI Matrice 600 Pro and software like Pix4Dmapper for their assessments.

Table 3.13 Maintenance Benefit Areas of D-RCM (Part II)

Benefit Area	Categories	Drone	Sensor type	Algorithm/Software
Unpaved Road Monitoring	Unpaved roads monitoring and prioritizing	Fixed wing	Nikon D800	SfM/Blender/Patch-Based Multi-View Stereo
		-	-	KNN
	Stone and gravel pavement condition monitoring	DJI Phantom 4 pro	Camera	CNN
		-	-	-
Pavement Condition Monitoring	Pavement distress monitoring	DJI Mavic 2 Pro	-	Canny algorithm
		-	-	CNN
		DJI Mavic 2 Pro	-	-
		-	-	Pix4Dmapper
		-	-	-
		-	-	-
		-	-	-
		-	-	-
		-	-	-
		Quadcopter	Nikon D5200 camera/ GoPro	Agisoft PhotoScan, Pix4D Pix4Dmapper Pro
		DJI Mavic Pro	12-megapixel	-
	Surface defect detection	DJI Phantom 3	Phantom camera	DEM
		DJI Phantom 4	-	LabelImg/Faster-RCNN
		-	-	CNN
		-	-	-
Network Mapping	Network mapping	-	-	U-Net
		Fixed wing UX5 Trimble	Sony NEX-5R	DTM generation algorithms
		-	-	-
Design & Infrastructure Management	Design and infrastructure management	-	-	-
		-	-	-

Studies on concrete bridge crack detection developed computationally efficient vision-based crack inspection methods using low-cost quadrotors and various mapping software. Studies about monitoring unpaved roads utilized drone imagery help address the challenges of unpaved road maintenance. Studies on pavement distress monitoring attempted to develop condition indices by processing pavement images using a convolutional neural network. Studies using drones to map road networks used depth-wise separable convolutions to enhance computational efficiency.

Table 3.14 is a comprehensive comparison between traditional and D-RCM methods. It provides data on the agency or reference, costs, time, and return on investment (ROI) for each method.

Table 3.14 Costs of Traditional and D-RCM Methods

App.	**Source**	**Traditional Method**				**Drone-Based Method**			**NPV**	**Cost Saving**	**Time Saving**	**ROI**	**BCR**
		Road Closure	Equip. Cost	Total Cost	Time & Crew	Equip. Cost	Total Cost	Time & Crew					
Bridge Inspection	MDOT [42]	-	-	$4,600	2 Crews 8 hours	-	$1,200	2 crews 1 hour	$3,400	74%	75%	283%	1.47
	MnDOT [43]	-	-	$59,000	8 days	-	$20,000	5 days	$39,000	66%	37.5%	195%	1.59
	McDOT [44]	-	-	$40,800	-	-	$19,900	-	$20,900	40%	-	105%	1.95
	ODOT [45]	$3,500	$2,800	$73,800	-	-	$63,600	-	$10,200	13%	-	16%	-0.3
	FDOT [46]	-	$2,500	$ 4,810	-	$2,000	$ 4,410	-	400	83%	-	9%	2.21
Under Bridge Inspection	[24]	-	-	$1,564	2 crews 1 day	-	$1,800	2 crews 1 day	$-236	-13%	0%	-13%	-9
	MnDOT [47]	$2,500/day	-	$6,080	2 crews 4 hours		$4,340	2 crews 4.5 hours	1740	40%	- 12.5%	40%	1.87
Intersection Inspection	TxDOT [48]	-	-	$8,000- $10.000	-	-	$5.000- $7.500	-	3000	37%	-	60%	-3.33
Stockpiles Survey	WVDOT [49]	-	-	$378,000	2-3 crews Collection: 3 days Processing: 2days	-	$35,000	2 crews Collection: 2-3 hours Processing: 10-12hours	$343,000	90%	75%	980%	9.8
Crash Scene Data	NCDOT [50]	$8,600/hr	-	$12,900	42 crews 15 days	-	$3,600	7 crews 9 days	$9,300	73%	90%	258%	0.91
Road Monitoring	Frontier Precision [51]			50,000	2 hours		21,000	½ hour	$29,000	58%	75%	138%	1.14
Survey	[52]	2 Lanes= $3,000		$4,600	Collection: 10 days Processing: 4 days	$50/hr	$250	Collection: 2 days Processing: 2days	$4,350	94%	71.5%	1740%	1.45

For example, for bridge inspections, the traditional method by MDOT costs $4,600 and takes eight hours, whereas the drone-based method costs $1,200 and takes only one hour. The table also includes metrics like net present value (NPV), cost saving, time saving, ROI, and benefit-cost ratio (BCR) to provide a full picture of the advantages of using drones.

Figure 3.14 graphically represents the percentage of cost savings across different applications. It highlights that the cost savings can be as high as 90% for stockpile surveys conducted by WVDOT.

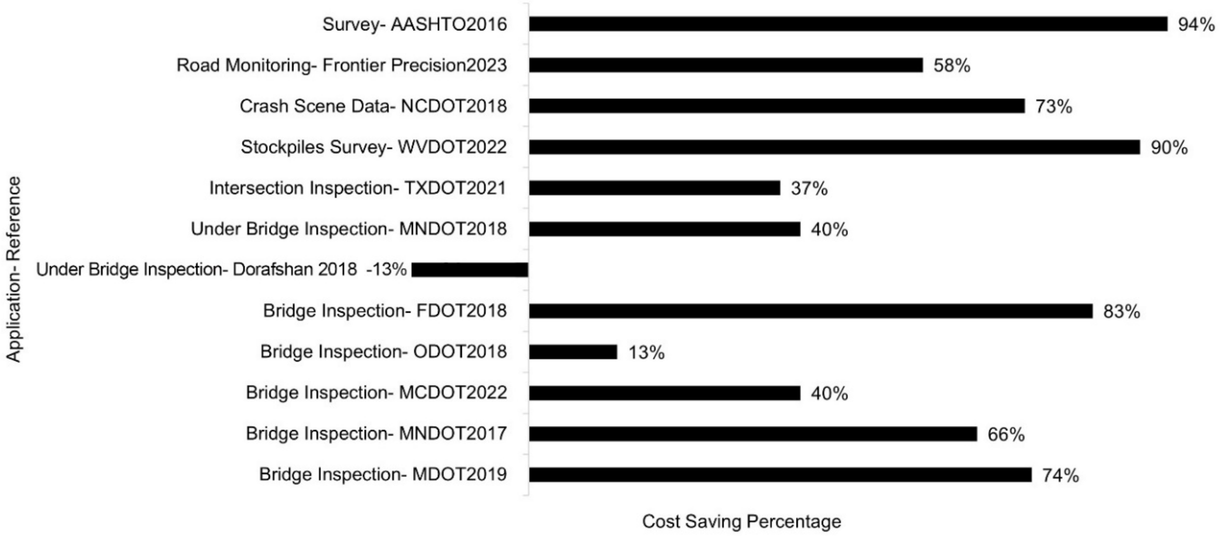

Figure 3.13 Cost saving percentages of D-RCM

Figure 3.14 illustrates the percentage of time saved when using drone-based methods. For instance, drone-based bridge inspections by MnDOT saved 75% of the time required by traditional methods.

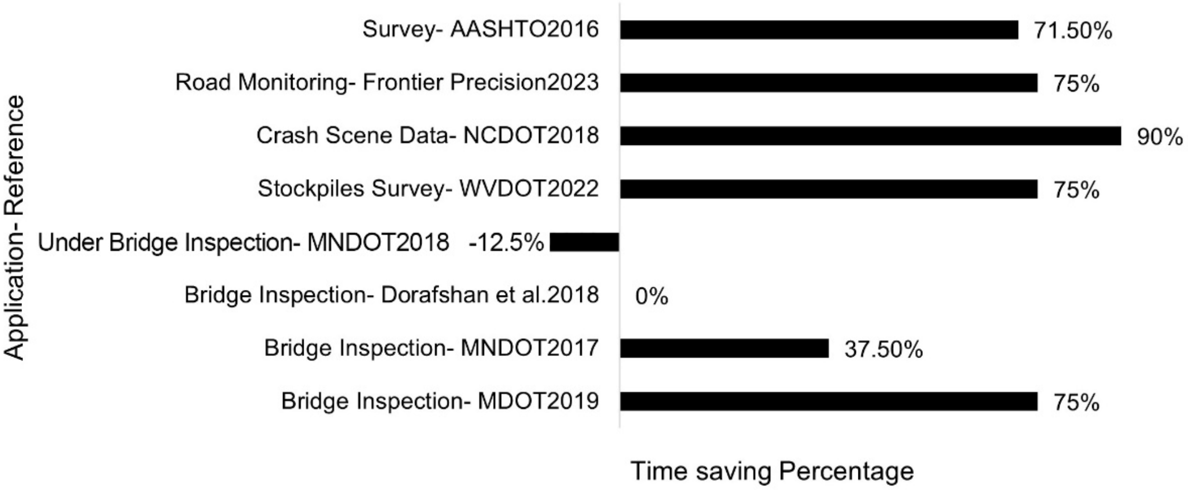

Figure 3.14 Time saving percentages of D-RCM

Figure 3.14 outlines the potential benefits of using drones in RCM. It categorizes the benefits into areas like reducing cost and time, improving safety, and other benefits like reducing traffic congestion. Each area further decomposed into specific advantages, such as reducing the number of crew members or eliminating the use of expensive vehicles.

Table 3.15 Potential Benefits of D-RCM

Potentials	Areas	Description
Reduce Cost and Time	Reduce data collection time Return the current cost of inspecting roads using old methods Improve safety Reduce number of crew members	Eliminate the use of expensive vehicles and hardware Reduce the number of crew members Eliminate the road or shoulder closure necessity Reduce the personnel time required onsite and to optimize data collection from 5 to 2 Eliminate the cost of driver and inspector Increase the efficiency Reduce the number of safeguards Increase scalability and inspection coverage Eliminate hazards and risks to improve productivity by 94% Reduce data collection time by 70% Obtain more detailed overview necessary to obtain more data of the entire asset
Improve Safety	Reduce accidents Produce more reliable information	Eliminate inspectors' exposure to hazards and risks Reduce the time of inspection for high traffic roads Conduct more frequent inspection of hard-to-reach areas like forest roads, under bridges, and pathways Provide more accurate details by 71% and reduce the risk of collapsing bridges or signs Reduce the number of accidents related to lane closure Eliminate the subjectivity involved in human inspections Reduce the risks associated with physical demands and large equipment operations Reduce the time spent by surveyors near highways, construction sites, or under unfavorable weather conditions.
Other Benefits	Reduce Traffic congestion Improve reliability	Provide real time, 360-degree, birds-eye and 3D views Eliminate traffic congestion Provide the possibility of the simultaneous collection of data on both horizontal and vertical signalization. Provide high-resolution views

Table 3.16 outlines the challenges and proposed solutions for D-RCM. It categorizes the challenges into technical, safety, regulatory, and organizational challenges, providing specific descriptions and corresponding solutions for each. This table serves as a roadmap for overcoming the barriers to implementing D-RCM effectively.

Table 3.16 Challenges and Solutions of D-RCM

Challenges	Description	Solutions
Technical challenges	Maintaining a visual line of sight Limited payload capacity and flight endurance Lighting conditions Limited weather resistance Real-time problems due to severe weather conditions, and distance from the receiver Drone speed can affect the image resolution Huge amount of collected data, and sophisticated analyzing methods	Add a terrain-following feature to flight planning and flight control software or apply for a Part 107 waiver to enable BVLOS operations Balance the battery capacity and weight to find the best spot Choose bright sunshine for mapping and overcast day for tree-covered areas Adjust the drone speed more than the wind speed. Or use a quadcopter with a high thrust-to-weight ratio Use post-processing Choose the ideal speed Process and analyze the data in the cloud and perform data analytics using GIS
Safety challenges	Hardware engineering errors like loose connections, faulty electronics Software engineering errors like programming errors, flawed algorithms, and signal interference Accidents or falls due to human errors. Collision with a structure while monitoring near it to obtain the best resolution The drone collides with a worker. Drone noise distracts workers, which can have secondary safety implications The fast-moving rotors of drones can cause dust emissions, which can affect the health and safety of workers Cyberattacks	An engineer's existence can be helpful in this situation A trained crew can reduce the human errors Use autopilot to avoid obstacles Maintain a visual line of sight and avoid inexperienced drone operators Train workers Prepare worksites to ensure drones work efficiently and safely around workers Using AI solutions and cyber-attack detection through ML
Regulatory challenges	Limited speed (under 100 mph) Limited altitude (below 400 ft) Inadequate regulatory support and industry standards Absence of regulations applicable to small drones Prior permission of flying drone Restriction of fly drones over people	Regulatory bodies worldwide are working to enable BVLOS and provide more flexible regulations. Apply a waiver to relax a few strict requirements Modification of traffic if exposed to traffic Provide permission before flying drone
Organizational challenges	Drone registration Inadequate capabilities, skills, and experience with drones Insurance obligations for pilot and drone Certification and training of pilots	Provide for drone registration and insurance Use a certified pilot Provide pilot insurance

3.3 Technology Assessment

This section outlines the systematic approach and analytical techniques employed to develop the propulsive efficiency index (PEX). It begins by detailing the data collection process, specifying the sources and criteria for selecting drone designs to be included in the study. Following this, the section elaborates on the statistical and computational methods used to derive the PEX and to analyze its distribution across various drone architectures and weight classes. The optimization algorithms and statistical tests applied to validate the PEX and its dependent parameters are also discussed. Figure 3.15 illustrates the overall workflow in the study.

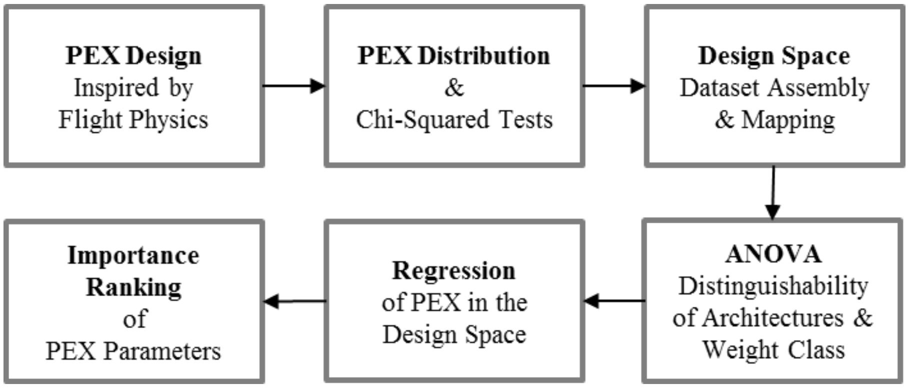

Figure 3.15 Workflow of the methods

Figure 3.16 serves as a visual guide to understanding the complex interplay between various aircraft design parameters and their impact on flight endurance. The figure uses gray-shaded boxes to indicate parameters that can be independently controlled based on design goals, while unshaded boxes represent dependent parameters. For instance, the maximum takeoff weight (MTOW) is influenced by the choice of airframe material, such as carbon fiber composite, and is directly proportional to factors like airframe volume, payload capacity, and the weight of other equipment like control hardware, wire harnesses, motors, and batteries.

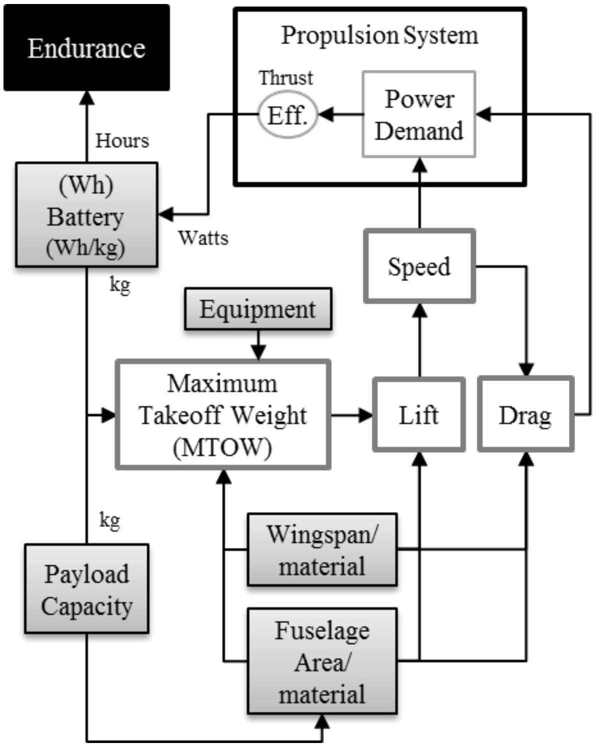

Figure 3.16 Interaction of aircraft design parameters

The workflow derived a PEX as follows:

$$\eta_{PEX} = \frac{L}{W} \times \frac{W_p}{W_m} \times \frac{R}{A} \tag{1}$$

The L/W ratio is the aspect ratio AR of the aircraft footprint. The PEX normalizes the horizontal flight range R by the vertical design altitude A.

Table 3.17 provides a comprehensive overview of the main types of winged vertical take-off and landing (VTOL) architectures. It categorizes them into five types: tilt rotor (TR), tilt wing (TW), transitioned thrust (TT), folding wing (FW), and fixed rotor (FR). For each type, the table lists the advantages and disadvantages, offering insights into the design trade-offs involved. For example, TR designs have more control and redundancy but come with the complexity and potential failure of tilting mechanisms.

Table 3.17 Winged VTOL Architecture Types

Type	Advantages	Disadvantages
Tilt rotor (TR). At least one set of rotors tilt to operate in both lifting and cruising modes.	Rotors are not idle in any mode—idle rotors are useless weight and may add drag unless enclosed. All rotors are available to maximize control and redundancy.	Weight, complexity, and possible failure of tilting mechanisms. Any propeller downwash onto the wings decreases lift efficiency. Transition from lift to cruise takes longer without separate cruise propellers.
Tilt wing (TW). At least one portion of the wing, with fixed rotors attached, tilts to achieve both lifting and cruising modes.	Rotors are not idle during cruise. Avoids tilting individual rotors for fewer mechanisms. All rotors are available to maximize control and redundancy. Avoids downwash.	Weight, complexity, and possible failure of tilting mechanisms. Transition from lift to cruise takes longer without separate cruise propellers. More susceptible to wind gusts while hovering. Placing batteries in the wing requires a sturdier tilt mechanism.
Transitioned thrust (TT). Fixed lift rotors become idle after transitioning to separate rotors for cruising.	Eliminates the weight, complexity, and possible failure of tilting mechanisms. Eliminates flight control complexity for rotor angle control and maintaining stability during tilting.	Exposed rotors can add to the drag. Rotor retraction or blade folding mechanisms can reduce drag but add weight and flight control complexity.
Folding wing (FW). At least one portion of the wing, with fixed rotors attached, folds to operate in both lifting and cruising modes.	Needs less ground footprint. No idle rotors in any mode. Accommodating more rotors on the folding members increase controllability.	Weight, complexity, and possible failure of folding mechanisms.
Fixed rotor (FR). Fixed position rotors adjust their relative speed to provide both lift and cruise operations.	Rotors are not idle in any mode. No tilting or folding mechanisms to increase weight or failure risk.	The airframe tilts up during vertical lift, which may cause discomfort if the cabin is not gimballed.

Table 3.18 serves as a legend for interpreting the dataset, explaining each column header and the units used. It covers parameters like the company manufacturing the aircraft, the model, the type of eVTOL architecture, and various performance metrics such as MTW, payload (P), and PEX. This table is essential for understanding the variables that are part of the constructed dataset.

Table 3.18 Description of the Data Table Headers

Parameters	Description	Units or category
Company	Manufacturer of aircraft	unitless
Model	Aircraft model	unitless
TY	Type of eVTOL architecture	TR (tilt rotor), TT (transitioned thrust), TW (tilt wing), folding wing (FW), fixed rotor (FR)
W	Width of aircraft	meters
L	Length of aircraft	meters
AR	Aspect ratio of length to width	None
MTW	Maximum takeoff weight	kilograms
P	Payload (people or cargo)	kilograms
R	Distance traveled at cruise speed	kilometers
C	Cruise speed	kilometers-per-hour (KPH)
T	Time spent in cruise mode	minutes
PEX	Propulsive efficiency index	unitless

Table 3.19 (part I) and Table 3.20 (part II) present the actual dataset, compiled from 45 manufacturers who have published all the required data to compute a PEX. The tables include a range of parameters, from the type of eVTOL architecture to specific performance metrics like cruise speed and time spent in cruise mode. Each entry also cites the data source, which can be from the manufacturer's website, patents, or investor presentations. The dataset is based on information available up to the end of 2021 and includes various types of data: measurements from full-scale prototypes, projections from sub-scale prototypes, and conceptual designs or simulations. In cases where companies did not disclose specific data like airframe dimensions, the author estimated values based on available resources like top-down views or patents. The dataset also standardizes certain variables for consistency. For example, it uses a typical cruise altitude of 10,000 feet for all entries where the cruise altitude was unavailable. Similarly, commercial airline estimates standardized the payload capacity when only the number of passengers and pilots was available.

Figure 3.17 is a graphical representation of the dataset discussed in the previous section, plotting payload capacity (in kilograms) against the reported cruise range (in kilometers). Each point on the graph corresponds to a specific aircraft model, and its position is determined by its payload and range capabilities as reported by the manufacturer. The primary objective of Figure 3.17 is to showcase the diversity in design capabilities across different architecture types in the current eVTOL landscape. It provides a visual snapshot of how various models compare in terms of their payload and range. However, it is crucial to note that these are manufacturer-reported values, which are not currently verifiable by the public. Additionally, as of the time the data were available, none of the designs received certification for commercial use. Nevertheless, by examining Figure 3.17, one can quickly grasp the range of design possibilities in terms of payload and cruise range, but it is essential to approach the data with a critical eye, considering the limitations and the stage of development for each aircraft model.

Table 3.19 eVTOL Data (Part I)

Company	Model	TY	W	L	AR	MTW	P	R	C	T	PEX	Source
ACS Aviation	Z-300	TW	8.0	7.1	0.89	1000.0	180.0	300.0	222.2	90.0	15.7	[53]
AIR EV	AIR ONE	FR	-	-	0.68	1170.0	200.0	177.0	160.9	60.0	6.8	[54]
Airbus	CityAirbus NG	TT	11.4	8.2	0.72	2200.0	453.5	80.0	120.0	40.0	3.9	[55]
Archer	Maker	TR	12.2	9.3	0.76	2052.2	544.2	96.5	241.4	24.0	6.4	[56]
Aurora Flight Sciences	Pegasus PAV	TT	8.5	9.1	1.07	798.2	224.9	80.5	180.2	26.8	8.0	[57]
Autoflight	V1500M	TT	12.8	10.3	0.80	1500.0	453.5	250.0	200.0	75.0	20.0	[58]
Autonomous Flight	Y6S	TR	6.1	6.7	1.10	907.0	226.8	128.7	201.1	38.4	11.6	[59]
Autonomous Flight	Y6S plus	TR	-	-	0.94	2630.4	657.6	128.7	201.1	38.4	9.9	[59]
Bartini Inc.	Bartini eVTOL	TR	5.5	5.5	1.00	1502.7	400.0	150.0	300.0	30.0	13.1	[60]
Bell	APT 70	FR	2.7	1.8	0.67	165.0	45.0	56.3	160.9	21.0	3.4	[61]
Bell	Nexus 4EX	TR	12.9	10.1	0.78	3718.8	544.2	96.5	241.4	24.0	3.6	[62]
Beta Technologies	Alia-250	TT	15.2	10.9	0.71	3174.1	680.3	463.0	194.5	142.9	23.2	[63]
Braunwagner	SkyCab	TT	12.0	10.1	0.84	2999.1	362.8	100.0	240.0	25.0	3.3	[64]
Digi Robotics	Droxi UAD-M20	TR	2.2	1.6	0.74	19.5	5.0	150.0	100.0	90.0	9.4	[65]
Dufour Aerospace	Aero3	TW	14.8	14.6	0.98	2799.5	749.7	120.7	350.0	20.7	10.4	[66]
EHang	VT-30	TT	12.5	6.8	0.54	881.2	181.4	300.0	180.0	100.0	11.0	[67]
eMagicAircraft	eMagic One	TT	7.7	7.2	0.94	400.0	145.1	144.0	144.0	60.0	16.1	[68]
Eve UAM	Eve	TT	11.0	13.0	1.18	1542.0	544.2	96.5	241.4	24.0	13.2	[69]
Flyter	PAC 720-200	TT	7.0	6.3	0.89	720.0	200.0	160.0	250.0	38.4	13.0	[70]
Grug Group	SBX	TR	10.3	7.6	0.74	2150.0	544.2	310.0	310.0	60.0	19.1	[71]
Horyzn Aerospace	Silencio Gamma	TT	3.6	2.0	0.54	12.0	2.0	51.0	70.0	40.0	1.5	[72]
Hyundai UAM	S-A1	TR	15.0	0.0	0.64	3668.5	544.2	99.8	289.6	20.7	3.1	[73]
Jaunt Air Mobility	Journey	TT	15.2	15.2	1.00	2721.1	544.2	144.8	281.6	30.9	9.5	[74]
Joby Aviation	S4	TR	11.6	6.4	0.55	2176.9	544.2	241.4	265.5	54.5	10.9	[75]
KARI	OPPAV	TR	7.0	6.2	0.88	650.0	100.0	50.0	200.0	15.0	2.2	[76]
Kitty Hawk	Heaviside	TR	6.1	4.7	0.77	374.6	113.4	160.9	289.6	25.0	12.3	[77]
Leap Aeronautics	Leap XE6	TT	12.0	8.0	0.67	2180.0	500.0	200.0	250.0	48.0	10.0	[78]

Table 3.20 eVTOL Data (Part II)

Company	Model	TY	W	L	AR	MTW	P	R	C	T	PEX	Source
Lilium	Jet (7 seat)	TR	13.9	8.5	0.61	3174.6	771.0	249.4	281.6	53.1	12.2	[79]
Micor Technologies	VAGEV	FW	6.1	5.1	0.83	600.0	200.0	80.0	130.0	36.9	7.2	[80]
Napoleon Aero	Napoleon Aero	TT	-	-	0.79	1500.0	400.0	100.0	241.4	24.9	6.9	[81]
Opener	BlackFly V3	FR	4.1	4.1	0.99	246.3	90.7	40.2	99.8	24.2	4.8	[82]
Orca Aerospace	Orca	TR	-	-	0.68	1814.1	300.0	140.0	204.0	41.2	5.2	[83]
Overair (Karem)	Butterfly	TR	13.7	10.0	0.73	3628.1	498.9	160.9	201.1	48.0	5.3	[84]
PteroDynamics	Transwing	FW	3.8	2.0	0.54	26.2	6.8	247.8	101.4	147.0	11.3	[85]
Samad Aerospace	S5M Cargo	TR	8.0	6.7	0.84	600.0	60.0	217.2	152.9	85.3	6.0	[86]
Skynet Project SRL	Genesys X-1	TR	6.0	3.5	0.58	139.7	49.9	99.8	180.2	33.2	6.8	[87]
Terrafugia	TF-2A	TT	7.5	7.2	0.96	1200.0	200.0	100.0	180.0	33.3	5.2	[88]
teTra Aviation	Mk-5	TT	8.6	6.2	0.71	567.0	78.9	75.6	108.0	42.0	2.5	[89]
Vertical Aerospace	VA-X4	TR	14.9	13.1	0.88	2267.6	449.9	160.9	321.8	30.0	9.2	[90]
Volocopter	Voloconnect	TT	-	-	1.00	1596.4	399.1	100.0	180.0	33.3	8.2	[91]
Voyzon Aerospace	e-VOTO	TR	8.0	4.3	0.53	726.8	226.8	125.0	250.0	30.0	6.8	[92]
VTOL Aviation India	Abhiyaan_ENU800	TT	10.8	7.5	0.69	800.0	200.0	250.0	180.0	60.0	14.2	[93]
Wing (Alphabet)	Wing	TT	1.0	1.3	1.30	6.3	1.2	19.3	104.4	11.1	1.5	[94]
Wingcopter	Wingcopter 198	TT	2.0	1.5	0.77	25.0	5.0	75.0	100.0	45.0	3.8	[95]
Wisk	Cora	TT	11.0	6.4	0.58	1451.2	181.4	40.2	160.9	15.0	1.0	[96]

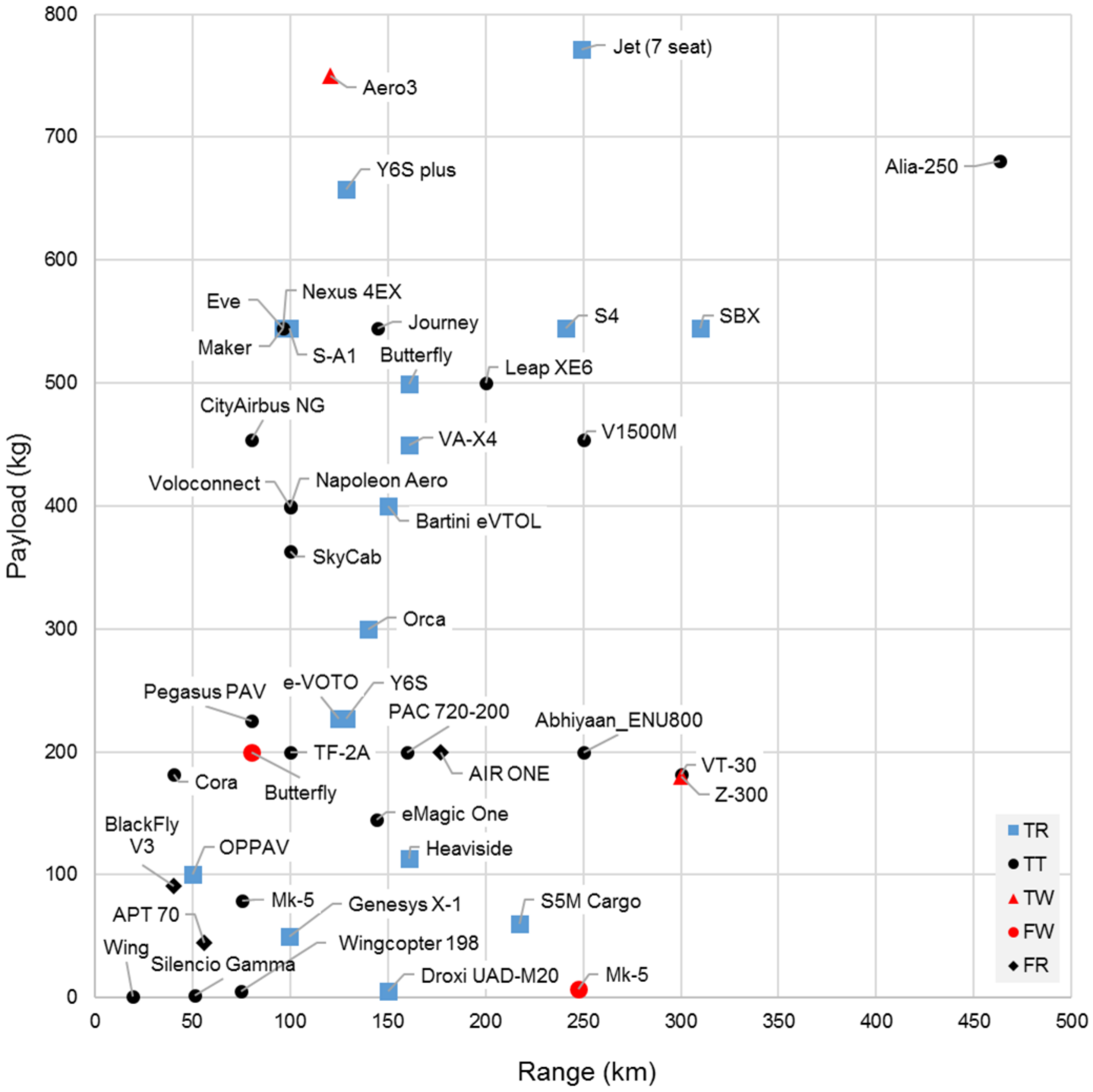

Figure 3.17 Aircraft model represented by the payload (kg) and range (km) reported

Figure 3.18 is a multi-part plot that shows histograms and best-fit distributions for five key parameters: a) PEX, b) range, c) speed, d) payload ratio (PR), and e) aspect ratio (AR). The inset in each sub-plot provides the mean (μ) and standard deviation (σ) for the distribution of each parameter. This figure aims to characterize the distribution of PEX and its independent parameters. The best-fit distributions were based on an optimization problem that calculates the best-fit distribution for each parameter. The optimization used a sum-of-squares (SOS) error minimization approach. The optimization procedure also calculated the Pearson's chi-squared statistic, which indicates the goodness of fit for each distribution.

Table 3.21 summarizes the statistics for each best-fit distribution, including the mean, standard deviation, and other statistical measures. It also provides the results of chi-squared tests to evaluate the null hypothesis (H0) for each distribution type. The table shows that none of the tests could reject the null hypothesis, indicating that the distributions fit the data well.

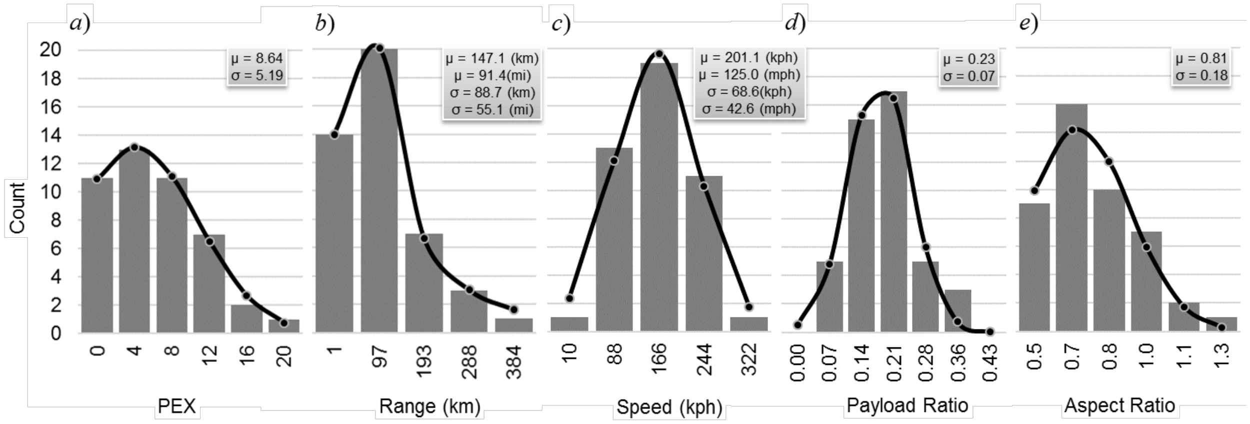

Figure 3.18 Distributions of a) PEX, b) Range, c) Speed, d) Payload Ratio, and e) Aspect Ratio

Table 3.21 summarizes the results of an ANOVA test for PEX, range, AR, and PR across all architecture types. The table shows there is no significant difference in the means of these parameters across different architectures.

Table 3.21 Parameters of the Performance Variable Distributions and Chi-squared Tests

Parameter	PEX	Range (km)	Speed (kph)	PR	AR
Mean	8.64	147.06	201.39	0.23	0.81
STD	5.19	88.66	68.66	0.07	0.18
Min	0.96	19.31	70.00	0.10	0.53
Max	23.25	462.99	350.00	0.37	1.30
CV	0.60	0.60	0.34	0.30	0.22
Skewness	0.74	1.33	0.07	0.13	0.56
Kurtosis	0.34	2.37	-0.69	-0.64	0.04
DOF	5	4	4	6	5
$\chi2$ Statistic	0.28	0.25	1.25	7.20	2.50
$\chi2$ p-value	0.99	0.99	0.87	0.31	0.77
H0	Normal	Lognormal	Normal	Normal	Normal
Reject H0	No	No	No	No	No

The mean values for range and speed were approximately 147 km (91 miles) and 201 kph (125 mph), respectively. The mean payload ratio accounted for approximately one-quarter of the MTOW. On average, aircraft were wider than their length with a mean length-to-width aspect ratio of 0.81. The coefficient of variation CV measured the standard deviation proportion of the mean, which was also an indication of the relative spread of each variable. The results show that the spread of the non-normalized range was 1.8, 2.0, and 2.7 times that of the speed, PR, and AR, respectively. That is, there was a larger spread in range than speed, PR, or AR in the design space. Consequently, the spread in PEX reflected the spread in range.

Figure 3.19 is a box plot that compares the PEX distribution for different eVTOL architecture types. It provides key statistics like mean, median, and quartile values. This figure characterizes the association between PEX and different eVTOL architectures.

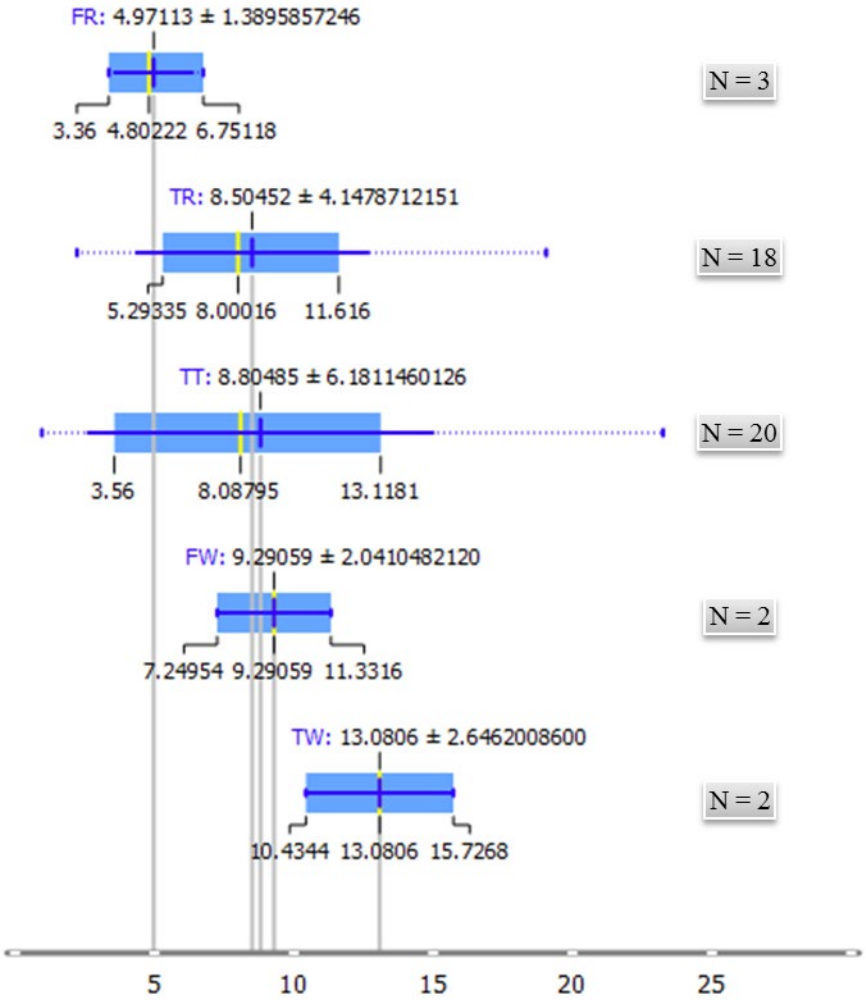

Figure 3.19 PEX distributions and ANOVA for the five drone architecture types

Table 3.22 summarizes the results of an ANOVA test for PEX, range, AR, and PR across all architecture types. The table shows there is no significant difference in the means of these parameters across different architectures.

Table 3.22 ANOVA Tests Across All Architecture Types

Parameter	ANOVA	p-value
PEX	0.740	0.570
Range	0.592	0.670
PR	0.706	0.593
AR	0.835	0.511

Figure 3.20 focuses on the PEX distributions for TR and TT architecture types, while Figure 3.21 does the same for FR, FW, and TW types. Both figures aim to provide a more detailed look at PEX distributions within specific architecture categories. Figure 3.22 is a box plot that shows the MTOW by weight class, and Figure 3.23 is a scatter plot that illustrates the co-distribution of PEX and MTOW by weight class. These figures characterize the association between aircraft weight and PEX. Figure 3.24 is another box plot that shows the PEX distribution by weight class. It complements the analysis by focusing solely on PEX across different weight categories. Table 3.1 summarizes the outcome of a linear regression model that aims to explain the PEX distribution in terms of its independent parameters: RA,

PR, and AR. The table provides coefficients for both normalized and non-normalized variables and shows that all coefficients are statistically significant.

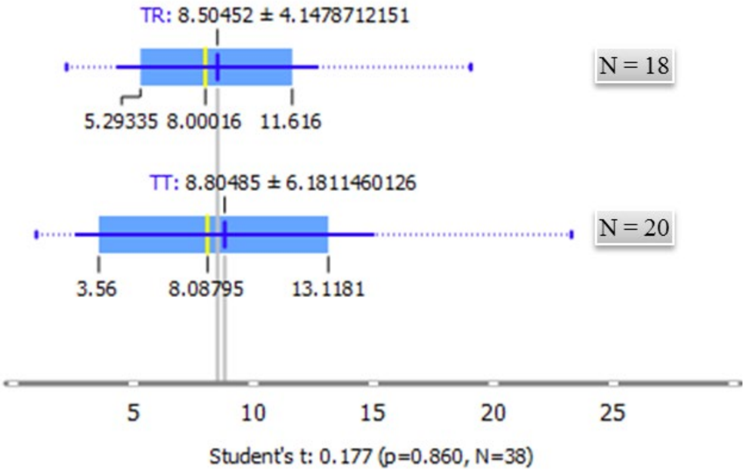

Figure 3.20 PEX distributions and t-test for the TR and TT drone architecture types

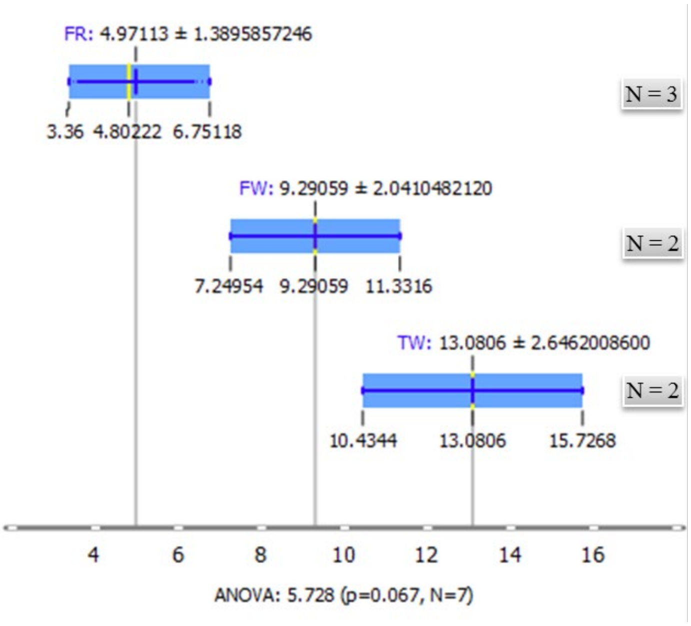

Figure 3.21 PEX distributions and ANOVA for the FR, FW, and TW drone architecture types

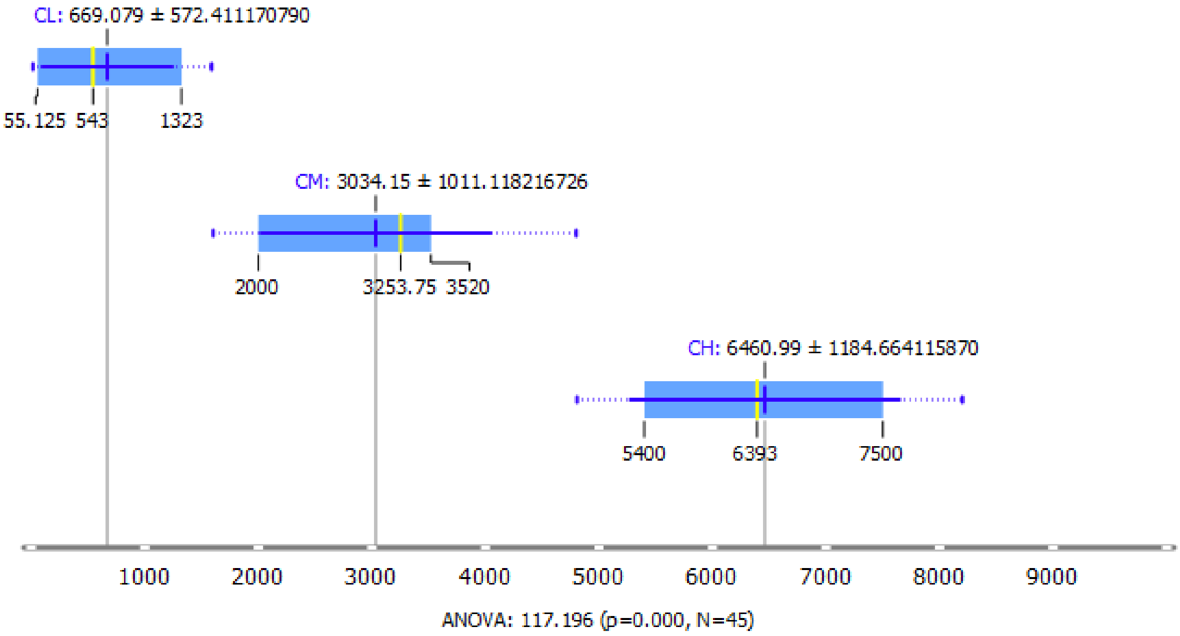

Figure 3.22 Box plot of MTOW (pounds) by weight class

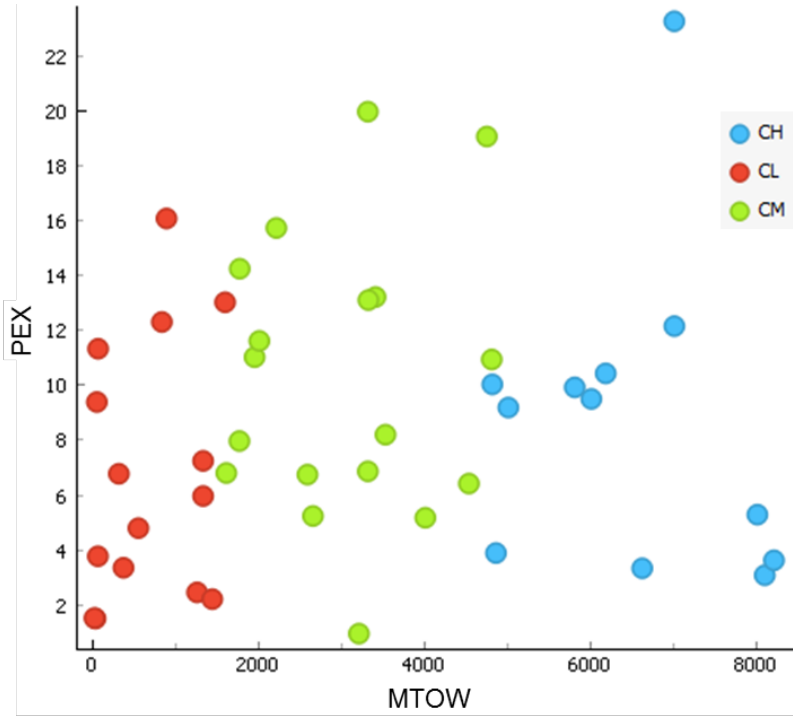

Figure 3.23 Scatter plot of PEX against MTOW by weight class

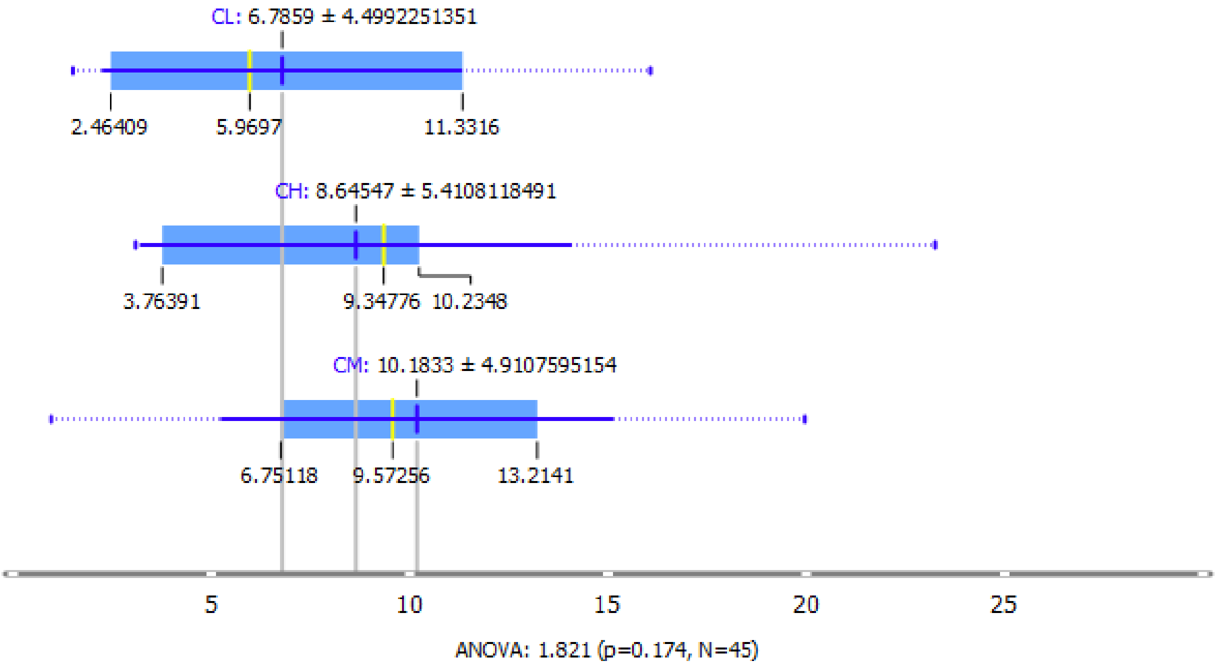

Figure 3.24 Box plot of PEX by weight class

Table 3.23 Parameters of the Regression Model

Coefficients	Unnormalized	[0, 1]	Std. Err.	t-statistic	p-value
Constant	-12.20	-4.04	0.71	-5.68	10^{-5}
RA	0.08	23.09	1.21	19.05	10^{-5}
PR	29.86	8.01	0.91	8.85	10^{-5}
AR	7.84	6.02	1.04	5.79	10^{-5}

Per the classic interpretation of R^2, the linear model estimated from parameter variations in the design space explained 0.919 or approximately 92% of the PEX variations. In other words, approximately 92% of the PEX variation in the design space fitted the linear model.

4. LIMITATIONS

This integrated study, while comprehensive, has limitations that span across the domains of railway inspection and monitoring (RIM), drone-based road condition monitoring (D-RCM), and drone technology development as follows:

Data Scarcity and Maturity: In the RIM and D-RCM sectors, the nascent state of drone and sensor technology limited the number of studies available for review. This restricted the comprehensiveness of the SLRs and may result in the omission of some elements, such as specific sensor payloads or emerging applications.

Lack of Quantifiable Metrics: Across all domains, there is a notable absence of standardized, quantifiable metrics for evaluating specific benefits, costs, and performance. This limitation makes it challenging to conduct precise cost-benefit analyses or to compare the efficacy of different technologies objectively.

Regulatory Uncertainty: The evolving regulatory landscape in all three domains poses a challenge for both current assessments and future projections. Regulatory decisions can significantly impact the rate of technology adoption and its subsequent ROI.

Technological Constraints: In the domain of drone technology development, the current non-existence of commercially operational heavy lift eVTOLs limits the validation of the introduced propulsion efficiency index (PEX). Similarly, in RIM and D-RCM, the industry must still address technological limitations such as battery life, payload capacity, and beyond visual line of sight (BVLOS) operations.

Geographical Bias: The country co-authorship analysis in the D-RCM domain revealed a strong influence of U.S. academic institutions, potentially limiting the global applicability of the findings.

Human Factors: The studies did not cover issues related to user acceptance, workforce training, and public perception, all of which are crucial for the widespread adoption of these technologies.

Dynamic Technological Landscape: The applications and technologies are rapidly evolving in all three domains. While this is promising, it also means that some of the data and findings could quickly become outdated.

Future research will aim to address these limitations by expanding the dataset to include more diverse and up-to-date sources, developing standardized metrics for evaluation, and incorporating human factors and regulatory considerations into the analysis. As conditioning monitoring and drone technologies mature and become more widely adopted, it will be crucial to update the findings to reflect the evolving landscape.

5. CONCLUSIONS

This comprehensive study amalgamated insights from systematic literature reviews (SLRs) on drone-based railway inspection and monitoring (RIM), road condition monitoring (D-RCM), and electric vertical takeoff and landing (eVTOL) aircraft. The SLRs underscored the rapid technological advancements in these domains despite existing barriers such as regulatory constraints, high initial costs, and workforce limitations.

In the realm of RIM and D-RCM, the SLRs revealed a lack of quantifiable metrics for specific benefits, marking this study a pioneering effort in categorizing and evaluating the advantages of drone technology. The analyses affirmed the economic and operational feasibility of drone-based approaches, emphasizing their potential to revolutionize business models and managerial practices. The technology's capacity to enhance inspection accuracy and frequency could lead to societal benefits, including improved maintenance practices and reduced accident rates.

The study assessing the drone technology landscape introduced a propulsion efficiency index (PEX) to fill the existing gap in objective performance metrics for eVTOL aircraft. Grounded in fundamental aerodynamic principles, the PEX offers a robust tool for performance comparison, requiring only three publicly accessible specifications: range, payload ratio, and aspect ratio. Statistical analyses indicated that these parameters collectively account for more than 90% of the variance in the PEX distribution, thereby serving as a valuable planning tool for future eVTOL performance.

The study identified several avenues for future research, including the need for more granular cost-benefit analyses and attitudes toward technology adoption in both RIM and D-RCM sectors. As the technology and regulatory landscape evolve, continual reassessment of return-on-investment (ROI) is imperative to capitalize on competitive advantages conferred by early adoption. In summary, this integrated study serves as a seminal guide for scholarly inquiry and practical deployment across the domains of RIM, D-RCM, and drone technology development, offering valuable insights for theoretical advancements, managerial decision-making, and societal impacts.

6. REFERENCES

[1] L. Hohnholz, "The Civilian Drones Market is Expected to Grow by USD 21,619.8 Million by 2030 with a 14.3% CAGR," 30 08 2022. [Online]. Available: https://eturbonews.com/the-civilian-drones-market-is-expected-to-grow-by-usd-21619-8-million-by-2030-with-a-14-3-cagr/#:~:text=The%20market%20for%20Civilian%20Drones,maintenance%20costs%2C%20and%20high%20mobility..

[2] A. O. Lebedev, V. V. Vasilev, B. N. Novgorodov and A. G. Paulish, "Computer Vision Controlling an Autonomous Unmanned Aerial Vehicle Flight over a Railway," in *2020 1st International Conference Problems of Informatics, Electronics, and Radio Engineering (PIERE)*, Novosibirsk, Russia, 2020.

[3] M. H. Frederiksen, O. A. Vrincianu, M. Mette and P. Knudsen, "Drones for inspection of infrastructure: Barriers, opportunities and successful uses," 2019.

[4] ASCE, "ASCE Infrastructure Report Card - Roads, American Society of Civil Engineers," 2019. [Online]. Available: https://www.infrastructurereportcard.org. [Accessed 2022 11 17].

[5] BBC Research, "Drone Technology and Global Markets," Business Communications Company (BCC) Inc., Wellesley, Massachusetts, 2020.

[6] Brandessence, "Drones Market By Type (Commercial Drones, Fixed-Wing Drones, VTOL Drones, Nano Drones And Others), By Application (Law Enforcement, Precision Agriculture, Media And Entertainment, Surveying And Mapping And Others), Industry Analysis, Trends, And Forecast," Brandessence Market Research and Consulting Pvt Ltd., London, 2021.

[7] R. Lineberger, D. Silver and A. Hussain, "Advanced Air Mobility: Can the United States afford to lose the race?," 2021.

[8] Y. Guo, D. Souders, S. Labi, S. Peeta, I. Benedyk and Y. Li, "Paving the way for autonomous Vehicles: Understanding autonomous vehicle adoption and vehicle fuel choice under user heterogeneity," *Transportation Research Part A: Policy and Practice,* vol. 154, no. 2021, pp. 364-398, 2021.

[9] H. Nakamura and Y. Kajikawa, "Regulation and innovation: How should small unmanned aerial vehicles be regulated?," *Technological Forecasting and Social Change,* vol. 128, 2018.

[10] M. Ayamga, S. Akaba and A. A. Nyaaba, "Multifaceted applicability of drones: A review," *Technological Forecasting and Social Change,* vol. 167, 2021.

[11] IEA, "The Role of Critical Minerals in Clean Energy Transitions," International Energy Agency (IEA), Paris, France, 2021.

[12] X. S. Zheng and D. Rutherford, "Reducing aircraft CO2 emissions: The role of U.S. federal, state, and local policies," International Council on Clean Transportation (ICCT), 2021.

[13] Ü. Yaprak, F. Kılıç and A. Okumuş, "Is the Covid-19 pandemic strong enough to change the online order delivery methods? Changes in the relationship between attitude and behavior towards order delivery by drone," *Technological Forecasting and Social Change,* vol. 169, 2021.

[14] O. Maghazei and M. Steinmann, "Drones in Railways: Exploring Current Applications and Future Scenarios Based on Action Research," *European Journal of Transport and Infrastructure Research,* vol. 20, no. 3, pp. 87-102, 2020.

[15] R. Kellermann, T. Biehle and L. Fischer, "Drones for parcel and passenger transportation: A literature review," *Transportation Research Interdisciplinary Perspectives,* vol. 4, p. 100088, 3 2020.

[16] S. Ahirwar, R. Swarnkar, S. Bhukya and G. Namwade, "Application of Drone in Agriculture," *International Journal of Current Microbiology and Applied Sciences,* vol. 8, no. 01, pp. 2500-2505, 2019.

[17] G. M. Dering, S. Micklethwaite, S. T. Thiele, S. A. Vollgger and A. R. Cruden, "Review of drones, photogrammetry and emerging sensor technology for the study of dykes: Best practises and future potential," *Journal of Volcanology and Geothermal Research,* vol. 373, pp. 148-166, 3 2019.

[18] A. Montanari, F. Kringberg, A. Valentini, C. Mascolo and A. Prorok, "Surveying areas in developing regions through context aware drone mobility," *DroNet 2018 - Proceedings of the 2018 ACM International Conference on Mobile Systems, Applications and Services,* pp. 27-32, 6 2018.

[19] I. Verdiesen, A. A. Tubella and V. Dignum, "Integrating comprehensive human oversight in drone deployment: A conceptual framework applied to the case of military surveillance drones," *Information (Switzerland),* vol. 12, no. 9, 9 2021.

[20] Mind Commerce, Commercial UAV Market by Drone Type, Use Cases and Applications, Supporting Infrastructure and Services 2022 - 2027, Mind commerce, 2022.

[21] H. J. Jung, J. H. Lee and I. H. Kim, "Challenging issues and solutions of bridge inspection technology using unmanned aerial vehicles," *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems,* vol. 10598, no. 1, p. 1059802, 2018.

[22] S. Feroz and S. A. Dabous, "UAV-Based Remote Sensing Applications for Bridge Condition Assessment," *Remote Sensing,* vol. 13, no. 9, 5 2021.

[23] H. Kim, S. Ham and I. Lee, "Real-time drone mapping based on reference images for vehicle facilitiey monitoring," *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives,* vol. 43, no. B2, pp. 43-48, 8 2020.

[24] S. Dorafshan and M. Maguire, "Bridge inspection: human performance, unmanned aerial systems and automation," *Journal of Civil Structural Health Monitoring,* vol. 8, no. 3, pp. 443-476, 7 2018.

[25] N. S. P. Peraka and K. P. Biligiri, "Pavement asset management systems and technologies: A review," *Automation in Construction,* vol. 119, 11 2020.

[26] W. Chen and M. Zheng, "Multi-objective optimization for pavement maintenance and rehabilitation decision-making: A critical review and future directions," *Automation in Construction,* vol. 130, 10 2021.

[27] F. Outay, H. A. Mengash and M. Adnan, "Applications of unmanned aerial vehicle (UAV) in road safety, traffic and highway infrastructure management: Recent advances and challenges," *Transportation Research Part A: Policy and Practice,* vol. 141, pp. 116-129, 11 2020.

[28] D. Kim, Y. Lee, S. Oh, Y. Park, J. Choi and D. Park, "Aerodynamic analysis and static stability analysis of Manned/unmanned distributed propulsion aircrafts using actuator methods," *Journal of Wind Engineering and Industrial Aerodynamics,* vol. 214, p. 104648, 2021.

[29] X. Yan, B. Lou, A. Xie, L. Chen and D. Zhang, "A Review of Advanced High-Speed Rotorcraft," *IOP Conference Series: Materials Science and Engineering,* vol. 1102, no. 1, 2021.

[30] G. Wilke, "Aerodynamic Performance of Two eVTOL Concepts," in *New Results in Numerical and Experimental Fluid Mechanics XII. DGLR 2018. Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol. 142, D. A., H. G., K. E., W. C., T. C. and J. S., Eds., Springer, Cham, 2020, pp. 392-402.

[31] S. Sripad and V. Viswanathan, "The promise of energy-efficient battery-powered urban aircraft," *Proceedings of the National Academy of Sciences of the United States of America,* vol. 118, no. 45, 2021.

[32] A. Bacchini, E. Cestino, B. V. Magill and D. Verstraete, "Impact of lift propeller drag on the performance of eVTOL lift+cruise aircraft," *Aerospace Science and Technology,* vol. 109, p. 106429, 2021.

[33] M. D. Pavel, "Understanding the control characteristics of electric vertical take-off and landing (eVTOL) aircraft for urban air mobility," *Aerospace Science and Technology,* p. 107143, 2021.

[34] S. S. Chauhan and J. R. R. A. Martins, "Tilt-Wing eVTOL Takeoff Trajectory Optimization," *Journal of Aircraft,* vol. 57, no. 1, pp. 93-112, 2020.

[35] G. Palaia, K. A. Salem, V. Cipolla, V. Binante and D. Zanetti, "A Conceptual Design Methodology for e-VTOL Aircraft for Urban Air Mobility," *Applied Sciences,* vol. 11, no. 22, p. 10815, 2021.

[36] A. A. Nyaaba and M. Ayamga, "Intricacies of medical drones in healthcare delivery: Implications for Africa," *Technology in Society,* 2021.

[37] A. A. Muhamat, A. F. Zulkifli, M. A. Ibrahim, S. Sulaiman, G. Subramaniam, S. Mohamad and Y. Suzuki, "Realising the Corporate Social Performance (CSP) of Takaful (Islamic Insurance) Operators through Drone-Assisted Disaster Victim Identification (DVI)," *Sustainablility,* vol. 14, no. 9, 2022.

[38] v. d. M. Deon, D. R. Burchfirld, T. D. Witt, K. P. Price and A. Sharda, "Drones in agriculture," *Advances in Agronomy,* vol. 162, pp. 1-30, 2020.

[39] T. Mühlhausen and N. Peinecke, "Capacity and Workload Effects of Integrating a Cargo Drone in the Airport Approach," *Automated Low-Altitude Air Delivery,* pp. 449-461, 2021.

[40] B. Ruzgienė, Č. Aksamitauskas, I. Daugėla, Š. Prokopimas, V. Puodžiukas and D. Rekus, "UAV photogrammetry for road surface modelling," *Baltic Journal of Road and Bridge Engineering,* vol. 10, no. 2, pp. 151-158, 2015.

[41] M. Ayamga, S. Akaba and A. A. Nyaaba, "Multifaceted applicability of drones: A review," *Technological Forecasting and Social Change,* 2021.

[42] AASHTO, "aashtovideo," 2019. [Online]. Available: https://www.youtube.com/watch?v=wk6_otGEOvM&t=83s. [Accessed 25 01 2023].

[43] J. L. Wells, B. Lovelace and T. Kalar, "Use of Unmanned Aircraft Systems for Bridge Inspections," *Journal of the Transportation Research Board,* vol. 2612, no. 1, 2017.

[44] C. Grazioso, "Using Drones for State Department of Transportations: Real-World Benefits, Use Cases and ROI," 2022. [Online]. Available: https://www.dartdrones.com/drones-for-state-department-of-transportations/. [Accessed 26 1 2023].

[45] D. T. Gillins, C. Parrish, M. N. Gillins and C. Simpson, "Eyes in the Sky: Bridge Inspections with Unmanned Aerial Vehicles," FHWA, Washington, DC, 2018.

[46] J. A. Bridge, P. G. Ifju, T. J. Whitley and A. P. Tomiczek, "Use of Small Unmanned Aerial Vehicles for Structural Inspection," FDOT, Tallahassee, FL, 2018.

[47] J. Wells and B. Lovelace, "Improving the Quality of Bridge Inspections Using Unmanned Aircraft Systems (UAS)," MDOT, Minnesota, 2018.

[48] A. J. Puppala and S. S. Congress, "Implementation of Unmanned Aerial Systems using Close-Range Photogrammetry Techniques (UAS-CRP) for Quantitative (Metric) and Qualitative (Inspection) Tasks Related to Roadway Assets and Infrastructures: Final Report," TxDOT, 2021.

[49] Aviationtoday, "How Transportation Departments Are Using Advanced Drone Technology for Infrastructure Inspections," 2022. [Online]. Available: https://www.aviationtoday.com/2022/08/02/transportation-departments-using-advanced-drone-technology-infrastructure-inspections/. [Accessed 19 1 2023].

[50] T. Dorsey, "35 State DOTs are Deploying Drones to Save Lives, Time and Money," AASHTO, 2018.

[51] C. Kemmesat and N. Stephenson, "UAS Advances in Transportation," Frontier Precision, 2023.

[52] AASHTO, "indd.adobe.com," 2016. [Online]. Available: https://indd.adobe.com/view/78d3b1d3-13c3-42c0-8bf2-75ea8c534d1a.

[53] ACS Aviation, "Product Specifications," 2021. [Online]. Available: https://www.acs-solutions.com.br/index.php/produtos. [Accessed 24 12 2021].

[54] AIR EV, "Pushing the Envelope of Electric Aviation," 2021. [Online]. Available: https://www.airev.aero/. [Accessed 24 12 2021].

[55] Airbus, "CityAirbus NextGen," 2021. [Online]. Available: https://www.airbus.com/en/innovation/zero-emission/urban-air-mobility/cityairbus-nextgen. [Accessed 24 12 2021].

[56] Archer Aviation Inc., "Introducing Maker," 2021. [Online]. Available: https://www.archer.com/maker. [Accessed 24 12 2021].

[57] Aurora Flight Sciences, "Urban Air Mobility," 2021. [Online]. Available: https://www.aurora.aero/urban-air-mobility/. [Accessed 24 12 2021].

[58] Autoflight, "Products," 2021. [Online]. Available: https://www.autoflight.com/en/products/. [Accessed 24 12 2021].

[59] Autonomous Flight, "Introducing the Revolutionary Y6S Plus - Six Seater Electric VTOL Aircraft," 2021. [Online]. Available: https://autonomousflight.com/. [Accessed 24 12 2021].

[60] Bartini, "The Future of Air Travel," 2021. [Online]. Available: https://www.bartini.aero/#product. [Accessed 24 12 2021].

[61] Bell, "Bell APT," 2021. [Online]. Available: https://www.bellflight.com/products/bell-apt. [Accessed 24 12 2021].

[62] Bell, "Bell Nexus," 2021. [Online]. Available: https://www.bellflight.com/products/bell-nexus. [Accessed 24 12 2021].

[63] BETA Technologies, "ALIA-250c," 2021. [Online]. Available: https://www.beta.team/aircraft/. [Accessed 24 12 2021].

[64] SkyCab, "Skycab Science. Not Fiction.," September 2021. [Online]. Available: https://sky-cab.net/. [Accessed 24 12 2021].

[65] D. Sigler, "Things are Looking up in Dubai," *Sustainable Skies,* 24 12 2018.

[66] Dufour Aerospace, "Aero3 - Welcome to Versatile and Efficient VTOL," 2021. [Online]. Available: https://www.dufour.aero/aero3. [Accessed 24 12 2021].

[67] EHang Holdings Ltd., "EHang Long-Range VT-30 AAV Makes Global Debut Before Zhuhai Airshow," 2021. [Online]. Available: https://ir.ehang.com/news-releases/news-release-details/ehang-long-range-vt-30-aav-makes-global-debut-zhuhai-airshow. [Accessed 24 12 2021].

[68] eMagic Aircraft, "eMagic One – An eVTOL that really works," 2021. [Online]. Available: https://emagic-aircraft.com/#details. [Accessed 24 12 2021].

[69] Eve UAM, LLC, "Eve Rio Experience," 2021. [Online]. Available: https://eveairmobility.com/rio-experience/. [Accessed 24 12 2021].

[70] Flyter, "Flyter Products," 2021. [Online]. Available: https://flyter.aero/en/products. [Accessed 24 12 2021].

[71] Grug Group LLC, "Grug Group Future Technologies," 2017. [Online]. Available: https://www.gruggroup.com/copy-of-charter-flights-2. [Accessed 24 12 2021].

[72] HORYZN, "Project Silencio," 2021. [Online]. Available: https://horyzn.org/silencio/. [Accessed 24 12 2021].

[73] Hyundai Motor Group, "Supernal Urban Air Mobility," 2021. [Online]. Available: https://supernal.aero/. [Accessed 24 12 2021].

[74] Jaunt Air Mobility LLC., "Commuting Reimagined," 2021. [Online]. Available: https://jauntairmobility.com/. [Accessed 24 12 2021].

[75] Joby Aviation, "Electric Aerial Ridesharing," 2021. [Online]. Available: https://www.jobyaviation.com/. [Accessed 24 12 2021].

[76] KARI, "Aviation," 2021. [Online]. Available: https://www.kari.re.kr/eng/sub03_01.do. [Accessed 24 12 2021].

[77] Kittyhawk, "Everyday Flight for Everyone," 2021. [Online]. Available: https://www.kittyhawk.aero/. [Accessed 24 12 2021].

[78] Leap Aeronautics, "The Product Performance," 2021. [Online]. Available: https://www.leapaero.com/#lastPage. [Accessed 24 12 2021].

[79] Lilium GMBH., "The First Electric Vertical Take-off and Landing Jet," 2021. [Online]. Available: https://lilium.com/jet. [Accessed 24 12 2021].

[80] Micor Technologies, "Variable Geometry VTOL Aircraft (VAGEV)," 2021. [Online]. Available: https://micortec.com/hybrid-electric-vtol-aircraft/. [Accessed 24 12 2021].

[81] Izvestia News, "Electric vertical takeoff aircraft developed in Russia," *Izvestia Newspaper,* 1 12 2017.

[82] Opener, "BlackFly Specifications," 2021. [Online]. Available: https://opener.aero/. [Accessed 24 12 2021].

[83] Orca Aerosapce, "Wings on Duty," 2021. [Online]. Available: https://www.orca-evtol.com/. [Accessed 24 12 2021].

[84] Overair, Inc., "Meet Butterfly," 2021. [Online]. Available: https://overair.com/product/. [Accessed 24 12 2021].

[85] Ptero Dynamics, Inc., "Transwing," 2021. [Online]. Available: https://www.pterodynamics.com/transwing. [Accessed 24 12 2021].

[86] Samad Aerospace, "Starling Cargo," 2021. [Online]. Available: https://www.samadaerospace.com/starling-cargo/. [Accessed 24 12 2021].

[87] L. Giurca, "Cost Effective Ultra-Efficient VTOL Aircraft Genesys X-2," 9 November 2021.

[88] Terrafugia, "Aviation Products and Services," Geely Technology Group, 2021. [Online]. Available: https://terrafugia.com/. [Accessed 24 12 2021].

[89] teTra Aviation Corp., "Mk-5 Specifications," 2021. [Online]. Available: https://www.tetra-aviation.com/mk-5. [Accessed 24 12 2021].

[90] Vertical Aerospace, "Faster, Quieter, Greener, Cheaper," Vertical Aerospace Group Ltd., 2021. [Online]. Available: https://vertical-aerospace.com/va-x4/. [Accessed 24 12 2021].

[91] S. Nicola, "Air-Taxi Startup Volocopter Unveils Four-Seater Suburban Shuttle," *Bloomberg,* 17 May 2021.

[92] Voyzon Aerospace, "Meet VOTO," 2021. [Online]. Available: http://www.evoto.in/. [Accessed 24 12 2021].

[93] VTOL Aviation India, "Abhiyaan_ENU800," VTOL Aviation India PVT. Ltd., 2021. [Online]. Available: https://vtolaviations.com/ABHIYAAN_ENU800.html. [Accessed 24 12 2021].

[94] Wing Aviation LLC., "Wing Delivery is Easy to Use," 2021. [Online]. Available: https://wing.com/how-it-works/. [Accessed 24 12 2021].

[95] Wingcopter, "Wingcopter 198," 2021. [Online]. Available: https://wingcopter.com/wingcopter-198. [Accessed 24 12 2021].

[96] Wisk Aero LLC., "Discover the Future of Urban Air Mobility," 2021. [Online]. Available: https://wisk.aero/aircraft/. [Accessed 24 12 2021].